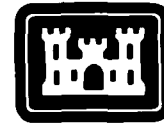


# Special Report 89-10

April 1989



**US Army Corps  
of Engineers**

Cold Regions Research &  
Engineering Laboratory

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## *Compacted-snow runways*

### *Guidelines for their design and construction in Antarctica*

David S. Russell-Head and William F. Budd

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Prepared for  
DIVISION OF POLAR PROGRAMS  
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## REPORT DOCUMENTATION PAGE

Form Approved  
OMB NO. 0704-0188  
Exp. Date: Jun 30, 1986

|   |  |  |   |                                |                            |
|---|--|--|---|--------------------------------|----------------------------|
| 1a. REPORT SECURITY CLASSIFICATION<br><b>Unclassified</b>   |  |  | 1b. RESTRICTIVE MARKINGS  |                                |                            |
| 2a. SECURITY CLASSIFICATION AUTHORITY   |  |  | 3. DISTRIBUTION/AVAILABILITY OF REPORT  |                                |                            |
| 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE   |  |  | Approved for public release; distribution is unlimited.                           |                                |                            |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S)   |  |  | 5. MONITORING ORGANIZATION REPORT NUMBER(S)<br><br>Special Report 89-10           |                                |                            |
| 6a. NAME OF PERFORMING ORGANIZATION<br><br>University of Melbourne  | 6b. OFFICE SYMBOL<br>(if applicable)     | 7a. NAME OF MONITORING ORGANIZATION<br>U.S. Army Cold Regions Research<br>and Engineering Laboratory |   |                                |                            |
| 6c. ADDRESS (City, State, and ZIP Code)<br><br>Melbourne, Australia   |  | 7b. ADDRESS (City, State, and ZIP Code)<br><br>72 Lyme Road<br>Hanover, N.H. 03755-1290              |   |                                |                            |
| 8a. NAME OF FUNDING/SPONSORING<br>ORGANIZATION<br>Division of Polar Programs<br>National Science Foundation   | 8b. OFFICE SYMBOL<br>(if applicable)     | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER<br><br>8 6000 70 704                                 |   |                                |                            |
| 8c. ADDRESS (City, State, and ZIP Code)<br><br>1800 G Street NW<br>Washington, D.C. 20550   |  | 10. SOURCE OF FUNDING NUMBERS  |   |                                |                            |
|   |  | PROGRAM<br>ELEMENT NO.   | PROJECT<br>NO.  | TASK<br>NO.                    | WORK UNIT<br>ACCESSION NO. |
| 11. TITLE (Include Security Classification)<br><br>Compacted-Snow Runways: Guidelines for their Design and Construction in Antarctica   |  |  |   |                                |                            |
| 12. PERSONAL AUTHOR(S)<br>Russell-Head, David S. and Budd, William F.   |  |  |   |                                |                            |
| 13a. TYPE OF REPORT   | 13b. TIME COVERED<br>FROM _____ TO _____ | 14. DATE OF REPORT (Year, Month, Day)<br>April 1989  |   | 15. PAGE COUNT<br>70           |                            |
| 16. SUPPLEMENTARY NOTATION  |  |  |   |                                |                            |
| 17. COSATI CODES  |  |  | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) |                                |                            |
| FIELD   | GROUP                                    | SUB-GROUP  | Antarctica  |                                |                            |
|   |  |  | Compacted-snow runways  |                                |                            |
|   |  |  | Runways   |                                |                            |
|   |  |  | Runway technology   |                                |                            |
|   |  |  | Snow  |                                |                            |
| 19. ABSTRACT (Continue on reverse if necessary and identify by block number)  |  |  |   |                                |                            |
| <p>Only small areas near the margins of the ice cap in Antarctica are ice-free, and only a few of these exposed sites are suitable for the construction of conventional runways. Wheeled aircraft have operated successfully on hard sea ice and exposed glacial ice, and skis have been fitted to a wide range of aircraft for use on snow. There has been a resurgence of interest in making snow runways suitable for use by conventional wheeled aircraft. Laboratory and field work has confirmed that low-density surface snow can be compacted in several ways to yield a strong, uniform, load-bearing pavement that can support heavy wheeled aircraft. The Soviets have constructed several full-scale runways in Antarctica. This report provides some of the technical background for the design and construction of compacted-snow runways in Antarctica. The technology is not particularly difficult, and it is likely that the next few decades will see substantial changes to Antarctic air transportation as more snow runways are constructed throughout the continent.</p> |  |  |   |                                |                            |
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT   |  |  | 21. ABSTRACT SECURITY CLASSIFICATION  |                                |                            |
| <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS  |  |  | Unclassified  |                                |                            |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>Dr. Malcolm Mellor   |  |  | 22b. TELEPHONE (Include Area Code)<br>603-646-4100                                | 22c. OFFICE SYMBOL<br>CECRL-EE |                            |

## PREFACE

This report was prepared by David S. Russell-Head and William F. Budd of the University of Melbourne (Australia). It draws on a range of internal reports and other documents that were generated as a result of runway studies by the Australian Antarctic Division at Casey Station, Antarctica. The work was carried out for CRREL as part of the 1987-88 program of Antarctic Engineering Services provided to the Division of Polar Programs, National Science Foundation. Antarctic Engineering Services are provided under a memorandum of agreement between NSF and CRREL. Funds for this work were covered by the designation 8 6000 70 704. The CRREL work is under the direction of Dr. Malcolm Mellor, Experimental Engineering Division.

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# Compacted-Snow Runways

## Guidelines for their Design and Construction in Antarctica

DAVID S. RUSSELL-HEAD AND WILLIAM F. BUDD

### INTRODUCTION

A major impediment to widespread use of heavy aircraft in Antarctica has been the lack of suitable landing strips for wheeled aircraft. The annual sea ice landing field at McMurdo has been used by wheeled C-130 Hercules and C-141 Starlifter aircraft. For inland operations, C-130 aircraft equipped with large skis have been used with considerable success.

In recent times, Soviet construction crews have built runways of compacted snow at Molodezhnaya and Novolazarevskaya for use by heavy wheeled aircraft (Fig. 1). Initially, Ilyushin 18D aircraft were used, and recently the much heavier Ilyushin 76T has been successfully introduced into the Soviet Antarctic transport system.

Australian interest in constructing a runway for

wheeled C-130 aircraft resulted in a trial construction program near Casey in 1983-84. Experiments with a snow mill, a motor grader and pneumatic-tired rollers were used to construct a pavement. Tests showed that the snow could be compacted to the required bearing capacity.

This report summarizes the technology involved in producing compressed snow pavements for use by heavy wheeled aircraft in Antarctica. The processes involved are relatively simple, but good knowledge of the local conditions and an understanding of the snow strengthening process are necessary before the technology can be successfully applied.

### HISTORY OF COMPACTED-SNOW RUNWAYS IN ANTARCTICA

The U.S. Navy constructed the first recorded compacted-snow runway in Antarctica in 1947 on the Ross Ice Shelf. Subsequent U.S. experience during the 1960s showed that it was possible to densify snow by disaggregation with pulvimixers or snow millers, and that higher densities result from using rollers on the disaggregated snow. Pavements were produced that supported C-130 aircraft (Moser and Sherwood 1967, Abele et al. 1968). The successful introduction of ski-equipped C-130 aircraft to Antarctica curtailed further U.S. work on compressed-snow runways for heavy wheeled aircraft.

At Molodezhnaya, Soviet experiments with conventional multi-tired rollers were started in the mid-1960s. During the 1970s, a trial runway pavement of high-density snow was produced, and testing showed it capable

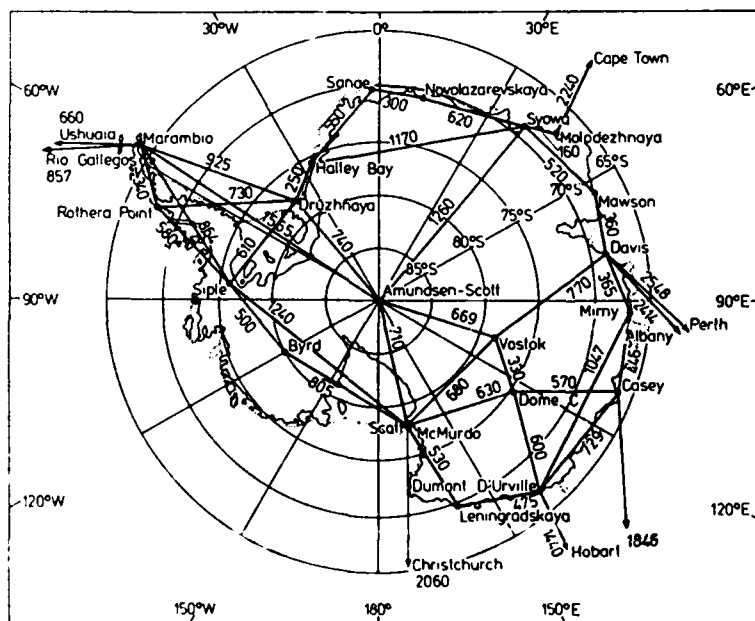


Figure 1. Map of Antarctica showing distances between stations (in nautical miles). (After SCAR Bulletin No. 56, May 1977.)

of supporting heavy wheeled aircraft (Aver'yanov et al. 1975). A runway was completed in 1980 and has been used for regular summer flights by Ilyushin 18D aircraft. In 1986, an Ilyushin 76T aircraft operated from compressed-snow runways at Molodezhnaya and Novolazarevskaya.

In the 1983–84 summer season, a trial construction of a compressed-snow pavement near Casey by an Australian team showed that a strong pavement could be made by using heavy multi-tired rollers to compress snow disaggregated by a snow miller (Appendix A). A full-scale plate bearing test showed that the trial pavement would adequately support the wheel loads of C-130H at maximum mass.

## MECHANICAL TESTING OF SNOW

### Wheel loads on pavements

When a pneumatic tire is loaded onto a pavement, the stress distribution produced in the pavement looks somewhat like a layered bulb (Fig. 2). The contact area is nearly circular and is approximately equal to the wheel load divided by the tire pressure.

The maximum vertical stress occurs directly under the tire contact area and is approximately equal to the tire pressure. Below a depth of about one diameter of the tire contact area, the pressure falls away quite quickly.

### Bearing tests

Snow mechanics shares some concepts and testing methods with soil mechanics. Two types of bearing tests in common use in soil testing have been used for testing snow. These are plate bearing tests and California Bearing Ratio tests. Both tests load a stiff circular area onto the soil and simulate the stress condition shown in Figure 2.

Plate bearing tests are carried out in the field situation where stiff circular plates of areas comparable to actual tire contact areas (i.e. 300–600 mm in diameter) are loaded to simulate the tire action on the soil. The resulting soil deflections are measured directly.

The California Bearing Ratio (CBR) test is a standardized soil test where a flat-faced piston is driven into a test sample at a constant speed. For laboratory testing, a sample of the material is constrained within a mold, but for field testing, the piston is driven directly into the surface material. The load on the piston is recorded as the test progresses. The CBR test can be viewed as a type

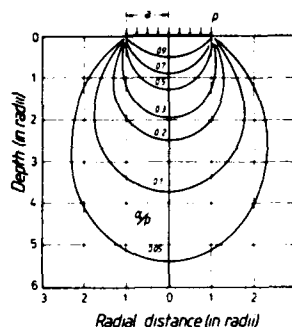


Figure 2. Contours of vertical compressive stress beneath a uniformly loaded circular area on a linear elastic half-space. This theoretical stress distribution is a good approximation of actual pavement stresses.

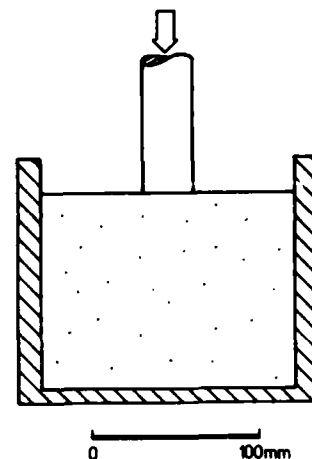


Figure 3. Laboratory CBR test, with a sample of the material constrained in a mold. A circular piston of 3 square inches (19.4 square cm) is driven into the test material.

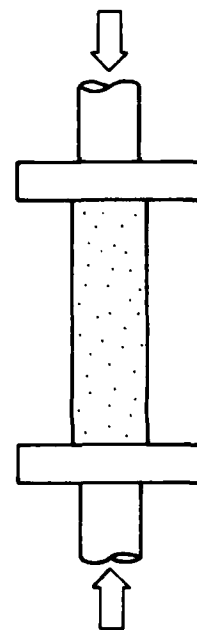
of small-scale plate test (Fig. 3). The CBR value is a measure of the resistance to penetration by the piston.

For snow testing, full-scale plate bearing tests are a field test only and are expensive to perform. The CBR test is less expensive (because of its small scale) and is usually done in the laboratory. Field CBR tests on snow are much more difficult to do than laboratory tests.

### Unconfined compression tests

In an unconfined compression test, a cylindrical sample of snow is placed between parallel platens of a testing machine, and the platens are then moved together, usually at a constant speed (Fig. 4). The mode of deformation varies according to the sample geometry, platen speed and snow age, temperature and density.

Figure 4. Unconfined compression tests, which are generally performed in a testing machine. The platens are usually driven together at constant speed, and a load cell indicates the force being exerted on the snow sample.



In some cases, particularly for aged, cold, high-density snow loaded at high platen speed, the snow sample breaks in a brittle fashion. Conversely, for fresh, warm, low-density snow loaded at low platen speed, the sample compresses and barrels but does not break.

Unconfined compression tests are not very appropriate for snow pavement design and testing because:

1. The test does not simulate the loading condition imposed by wheels.
2. The test has not been standardized with respect to sample size and platen speed.
3. It is not possible to assign an unconfined compressive strength value to a snow sample that does not break but merely consolidates.

### Compaction tests

There are no standardized tests for measuring the compactibility of snow. However, soil mechanics methods can be used to some extent in snow compaction studies.

Standard compaction hammers, developed for the preparation of soil test samples, can be used to gauge the compactibility of snow. A measure of the compactibility is the required energy (from the

hammer blows) per unit mass of the snow to produce a certain density or density increase.

Unconfined compression tests, if executed at slow platen speeds, can result in the test sample being compacted rather than broken, and some useful compactibility information may be gained from the test. A confined type of compression test may produce a better simulation of the action of a compaction roller wheel than the unconfined test, and it also may be more realistic than the hammer impact type of compaction test.

### Rammsonde tests

The Swiss rammsonde is a portable impact penetrometer that has had wide use in glaciological studies. It was originally used to gauge the density of snow at depth and has often been used in stratigraphic studies of the surface snow and firn in Antarctica (Fig. 5).

The instrument consists of a 60° conical tip of 40-mm maximum diameter mounted on a 19-mm-diameter stainless steel shaft 1 m long. A hollow cylindrical hammer slides down a guide to strike the top of the shaft. Hammer masses of 1, 2 or 3 kg are normally used. The rammsonde number is a measure of the force required to penetrate the snow.

### Clegg impact tests

During the 1970s an impact testing device was developed to provide a rapid test of soil bearing properties, as an alternative to the CBR test. A correlation of Clegg Impact Value (CIV) and CBR has been given for soils (Clegg 1980).

The Clegg device comprises a 4.5-kg flat-faced impact hammer, a guide tube and an electronic system to record the impact of the hammer onto the test surface. The simplicity of the device and its operation are in contrast to the complexity of the field CBR apparatus and procedure.

Recently CIV measurements have been made in the McMurdo area (Lee et al. 1986). As yet, no direct correlation between CIV and CBR for snow has been determined.

## MECHANICAL PROPERTIES OF SNOW

Laboratory and field tests on snow have shown the overriding importance of snow density on the mechanical properties of compressed snow. Figure 6 summarizes the relationship between rammsonde value, CBR and snow density. The effect of temperature is not easily quantifiable. In general the colder the snow, the stronger it is. However, for



Figure 5. Rammsonde penetrometer in use in Antarctica.

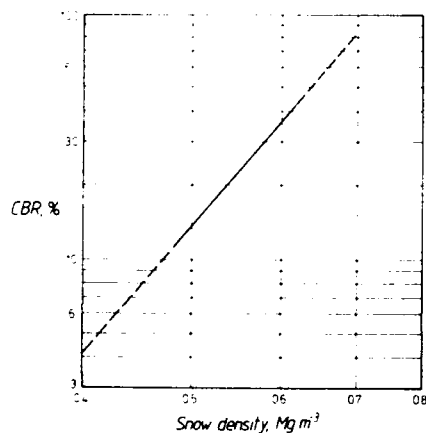
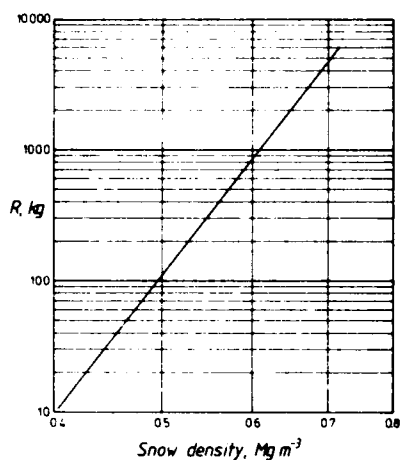


Figure 6. Rammsonde hardness and CBR values of field snow, which are strongly dependent on snow density.

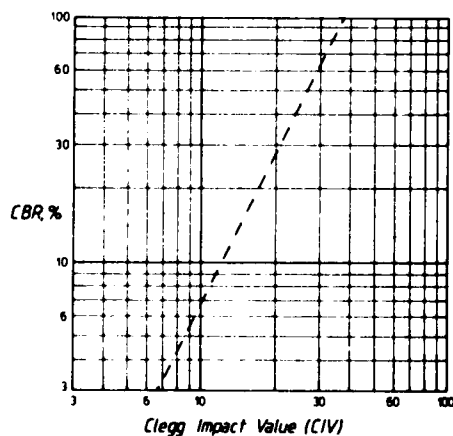


Figure 7. Relationship between CBR and CIV for soils, as reported by Clegg (1980).

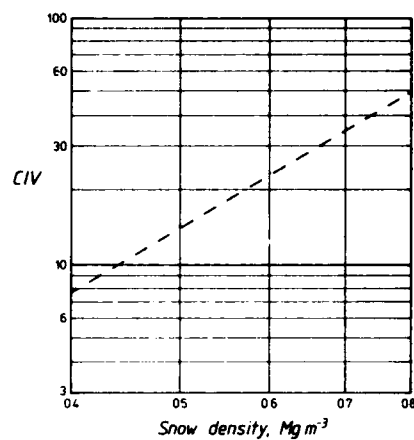


Figure 8. Variation of CIV value with snow density if the relationship between CBR and CIV is the same for snow as it is for soils.

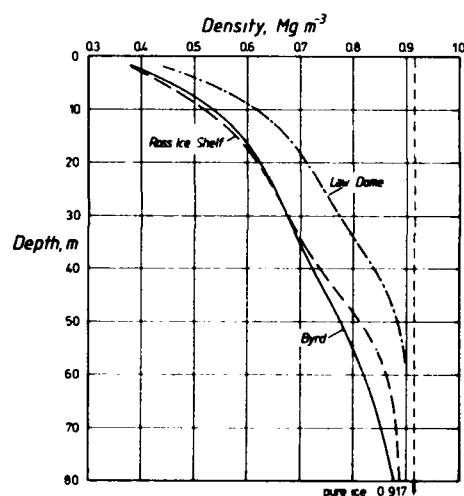


Figure 9. Density vs depth at several sites in Antarctica. Typically the density of snow increases with depth at net accumulation sites.

disaggregated snow the colder it is, the longer the time it takes for the grains to sinter together.

In Figure 7 the relationship between CIV and CBR as found for soils (Clegg 1980) is shown. If a similar relationship were to hold for snow, the relationship between snow density and CIV would be that shown in Figure 8.

In Antarctica it is usual for the density of the snow to increase with depth. This is the result of a combination of processes including evaporation, wind action, radiation, sintering and compression. Figure 9 shows the density-depth profile at a number of sites in Antarctica. The profiles are



typical of net accumulation sites, where the surface snow of low density (approx  $0.35 \text{ Mg m}^{-3}$ ) is gradually buried and densified. The maximum possible density is  $0.917 \text{ Mg m}^{-3}$ , which is the density of pure, air-free ice.

The load bearing capacity of snow of about  $0.6 \text{ Mg m}^{-3}$  density is adequate for an infrequently used airstrip. It is only the near-surface snow that has low density, and the construction of a pavement for wheeled aircraft essentially involves the strengthening by densification of the surface layer of snow.

## COMPRESSED-SNOW RUNWAY TECHNOLOGY

### Recent developments

The Soviets have had the most experience in constructing and operating from compressed snow runways in Antarctica. Unfortunately very little published information has become available, but the current state of their technology seems to be:

1. Compressed-snow runways have been constructed at Molodezhnaya and Novolazarevskaya.
2. IL-18D and IL-76T aircraft have operated successfully from these runways.
3. A compressed-snow runway is being constructed at Vostok.
4. The preferred construction technique is to use towed road-working pneumatic-tired rollers to compact the snow.
5. The most efficient compaction occurs when the snow is warmest.

Australian experience is quite limited by comparison to the Soviets'. A trial construction program was undertaken on the Law Dome near Casey in the 1983-84 summer. The equipment used included a D7 Caterpillar tractor, a 14G Caterpillar motor grader, a Schmidt snow miller, 20-tonne and 38-tonne self-propelled pneumatic-tired rollers, and a small disk plow.

The equipment was tried out in a number of modes in an effort to develop a suitable construction method. A section of test pavement was constructed, and a full-scale plate load test showed that the pavement was adequately strong for operation by fully-laden C-130 aircraft. Details of the snow testing program have been published as several Melbourne University Programme in Antarctic Studies (MUPAS) Reports, one of which is included as Appendix A. The general outcome of the trials can be summarized:

1. An adequately strong pavement can be constructed at Lanyon Junction on the Law Dome near Casey.
2. Snow compaction is best achieved by pneumatic-tired rollers.
3. Snow compaction is most efficient when the snow is just moist.
4. A very large towed roller should be built for constructing and maintaining a full-scale runway.

### Design, construction and testing of compacted-snow runways

The experience gained in the Casey field trials has been reviewed in the light of pavement design in general and laboratory work in snow mechanics. Two reports, included here as Appendices B and C, summarize the outlook at the present stage for designing, constructing and testing compacted-snow pavements.

Those two reports, presented in the form of manuals, should be seen as early steps on the way to developing a comprehensive understanding of compressed-snow runway technology. One can be quite confident that compressed-snow runways are realistic for many sites in Antarctica and that their construction will become more straightforward with the inevitable advances in the technology. The major points of the two reports are summarized below.

The basic purpose of the construction equipment is to compact snow to a sufficiently high density so that it forms a pavement that can withstand aircraft wheel loads. Figure 10 shows the strong influence of snow density on CBR. Some of the construction equipment used in the 1983-84 Casey trials is shown in Figure 11.

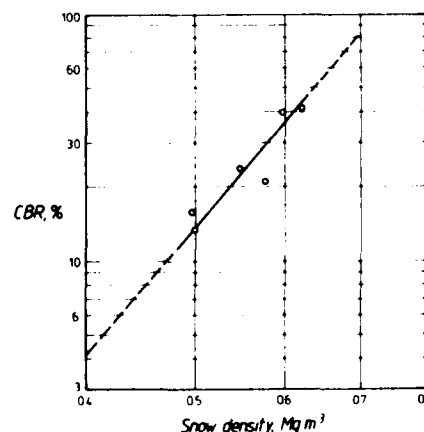


Figure 10. CBR strength vs snow density.

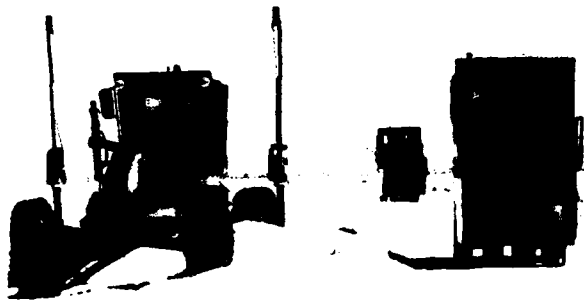


Figure 11. Self-propelled pneumatic-tired rollers used in the Casey trials. The motor grader was fitted with laser leveling sensors.

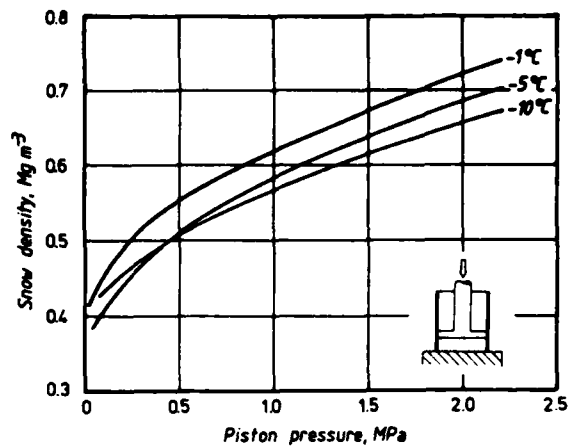


Figure 12. Results of laboratory tests that confirm that snow is easier to compact at higher temperatures.

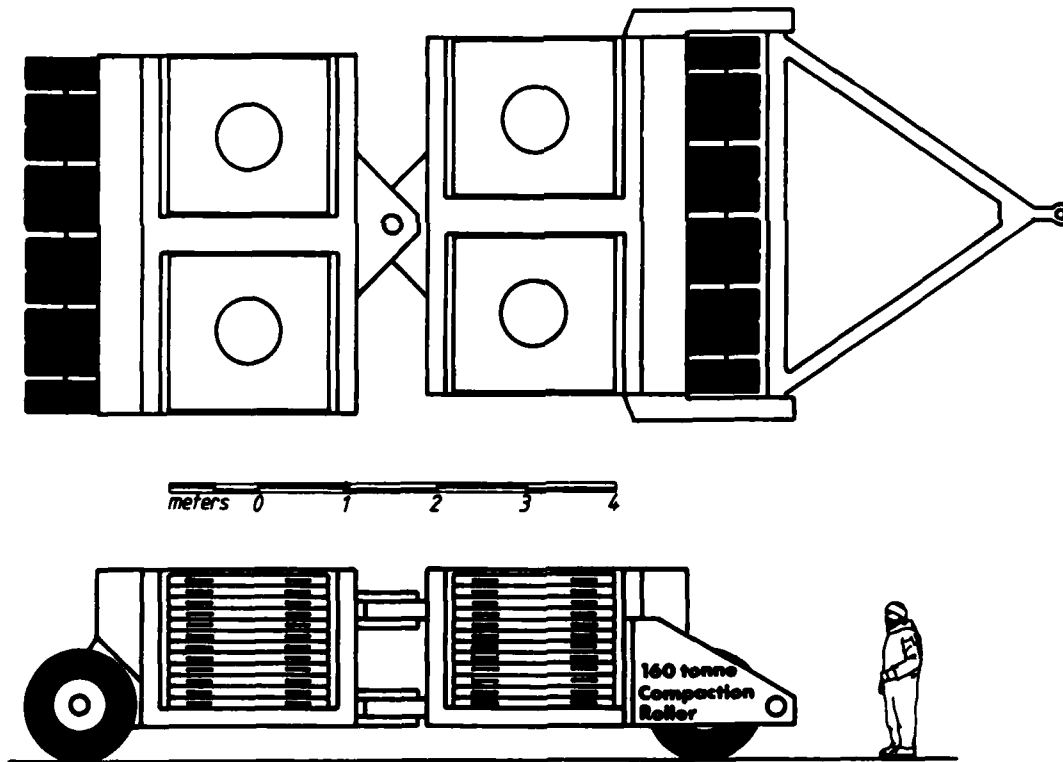


Figure 13. Large compaction roller specially designed for compacting snow runways.

The efficiency of the snow compaction depends on tire pressure and snow temperature. The maximum pressure for compaction tires is around 1000 kPa (1 MPa). Laboratory tests suggest that a density of about  $0.6 \text{ Mg m}^{-3}$  is achievable for tire pressures of 1000 kPa and snow temperatures above  $-5^\circ\text{C}$

(Fig. 12). The CBR of snow of this density is about 35 (Fig. 10).

Figure 13 shows a suggested form of a specially built compaction roller. The concept is for a large towed roller that can be dismantled into parts for air freighting by C-130 aircraft. The stackable steel

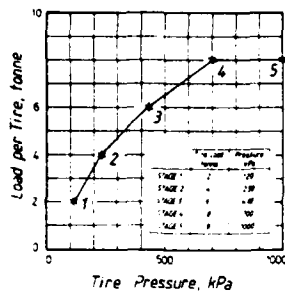
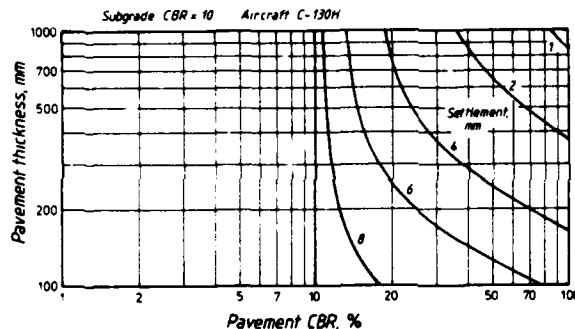
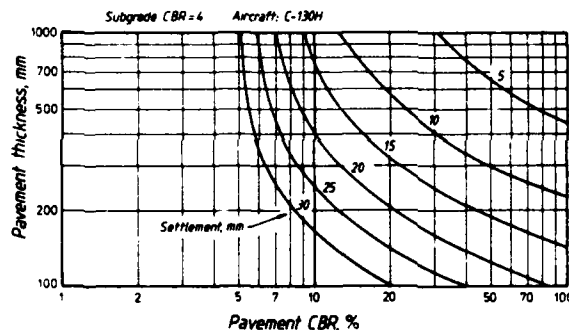


Figure 14. Sequence of increase in roller loads and tire pressures during construction.



a. Subgrade CBR = 10.



b. Subgrade CBR = 4.

Figure 15. Design curves showing the importance of subgrade CBR as well as pavement CBR on expected settlement.

dead weights can be handled by a tracked loader fitted with forks. Figure 14 shows the suggested sequence of increase in load and tire pressure during the construction program.

Figure 15 is from the design manual and shows the strong influence of subgrade CBR on required pavement thickness. Figure 15a is for a subgrade CBR of 10, which corresponds to the Casey site; Figure 15b is for a subgrade CBR of 4, which is an estimate of the situation at the South Pole. Proof rolling is an important aspect of runway construction, testing and maintenance. The design of a C-130 proof roller shown in Figure 16 uses C-130 rims and tires fitted to a specially built chassis that accommodates the steel dead weights of the compaction roller. The wheel base and track of the proof roller is the same as the that for the C-130 aircraft.

Figure 17 shows the results of a full-scale dead-weight plate test on the Casey test pavement made in the 1983-84 summer. The settlement is similar to a creep curve where there is an initial settlement followed by further settlement at a rate that decreases with time. The steel test plate had been placed on a grooved surface (Fig. 18), and the initial settlements shown in Figure 17 are higher than what would be expected if the surface had been smooth. When the aircraft is moving, the loading time is less than a second and one would expect the wheel ruts in the Casey test pavement to be only a few millimeters. The test pavement was milled through to see what had happened in the plate test zone (Fig. 19). No cracking could be seen; the snow pavement had been simply further compacted.

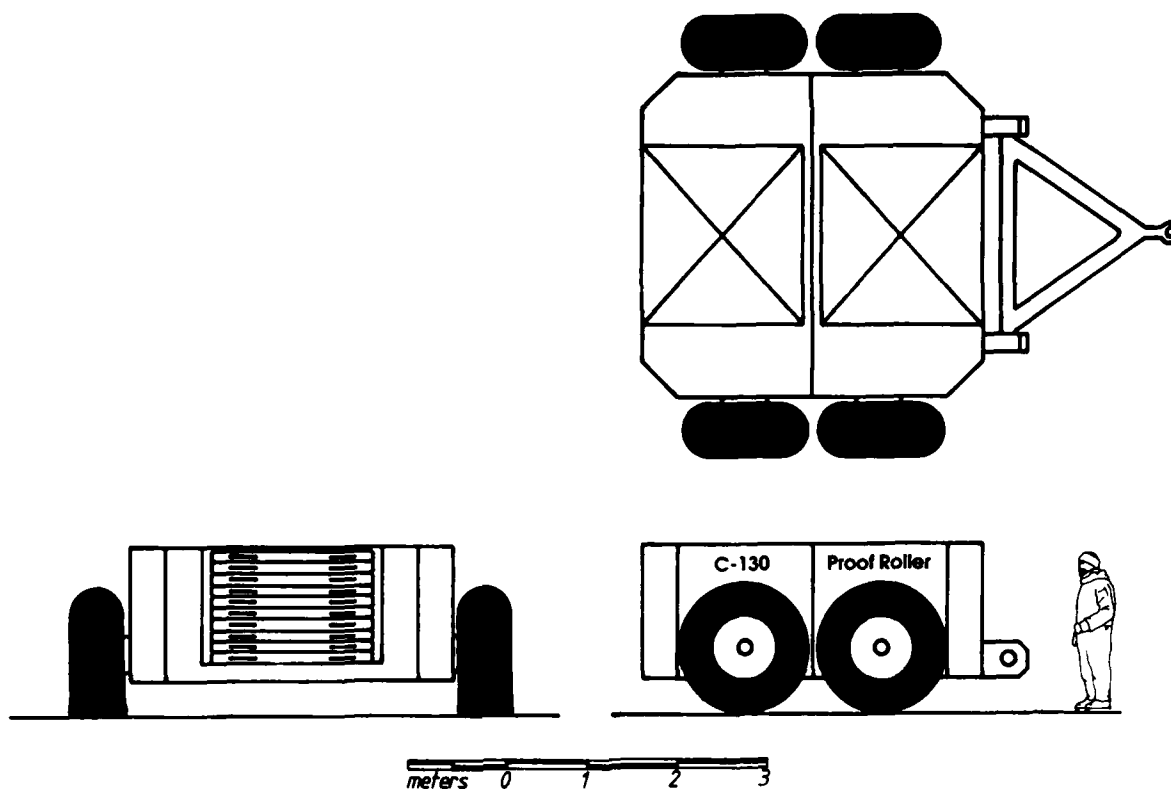
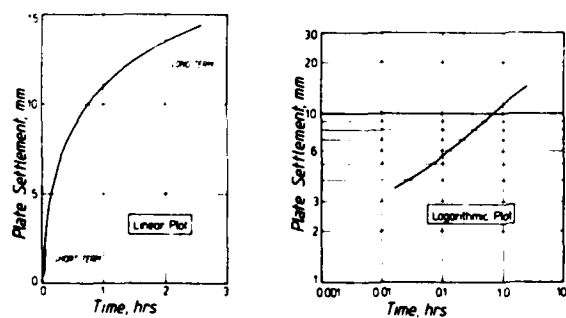


Figure 16. Proof roller that mimics the aircraft load and landing gear for monitoring the adequacy of the pavement.



a. Linear plot.

b. Logarithmic plot.

Figure 17. Settlement of a fully-laden full-scale C-130 test plate on the Casey test pavement, which increased with time but at a diminishing rate. The short-term settlement is a few millimeters. The settlement in the long term (more than an hour) is several tens of millimeters.



Figure 18. Test plate and pavement after 2.5 hours.



Figure 19. Cross section of the pavement through the test plate zone.

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## APPENDIX A. CASEY SNOW RUNWAY TESTS, 1983-84\*

### SUMMARY

This appendix describes the methods and equipment used to collect data at the proposed site of the Casey compressed-snow runway during the 1983-84 summer season, and includes some analysis of the data obtained. The data used in this appendix are tabulated in a companion report (Russell-Head et al. 1984).

The main purpose of the snow testing work was to assess the condition and strength of the in situ snow and the snow processed to form a pavement. The stratigraphy, density and particle size distributions for the in situ material, new and aged drift snow, compacted natural snow, processed snow, and compacted processed snow were obtained. Rammsonde and Scala penetrometer tests on the same types of snow were also obtained. Snow strength was assessed by California Bearing Ratio (CBR) tests. Seventeen CBR tests were made on snow with densities in the 0.4-0.7 Mg m<sup>-3</sup> range. The average CBR of the in situ material was about 10%. The CBR of the pavement material after a few day's hardening was about 40%.

Relationships between CBR, rammsonde hardness and density have been found for the in situ material. They follow the general pattern of results from other sites and laboratory tests. A newly developed small-diameter rammsonde needs to be standardized for

use in profiling dense snow. The performance of a 200-mm-thick test pavement of 0.65 Mg m<sup>-3</sup> density was assessed by using a steel plate 600 mm in diameter loaded to 16.2 Mg, equivalent to a pressure of 562 kPa (82 psi). The average settlement after a 2.5-hour test period was less than 10 mm.

The results of the 1983-84 testing program demonstrate that a pavement strong enough to support C-130 aircraft loads can be constructed at the Lanyon Junction site with the types of snow-processing and road-working equipment used for the trials.

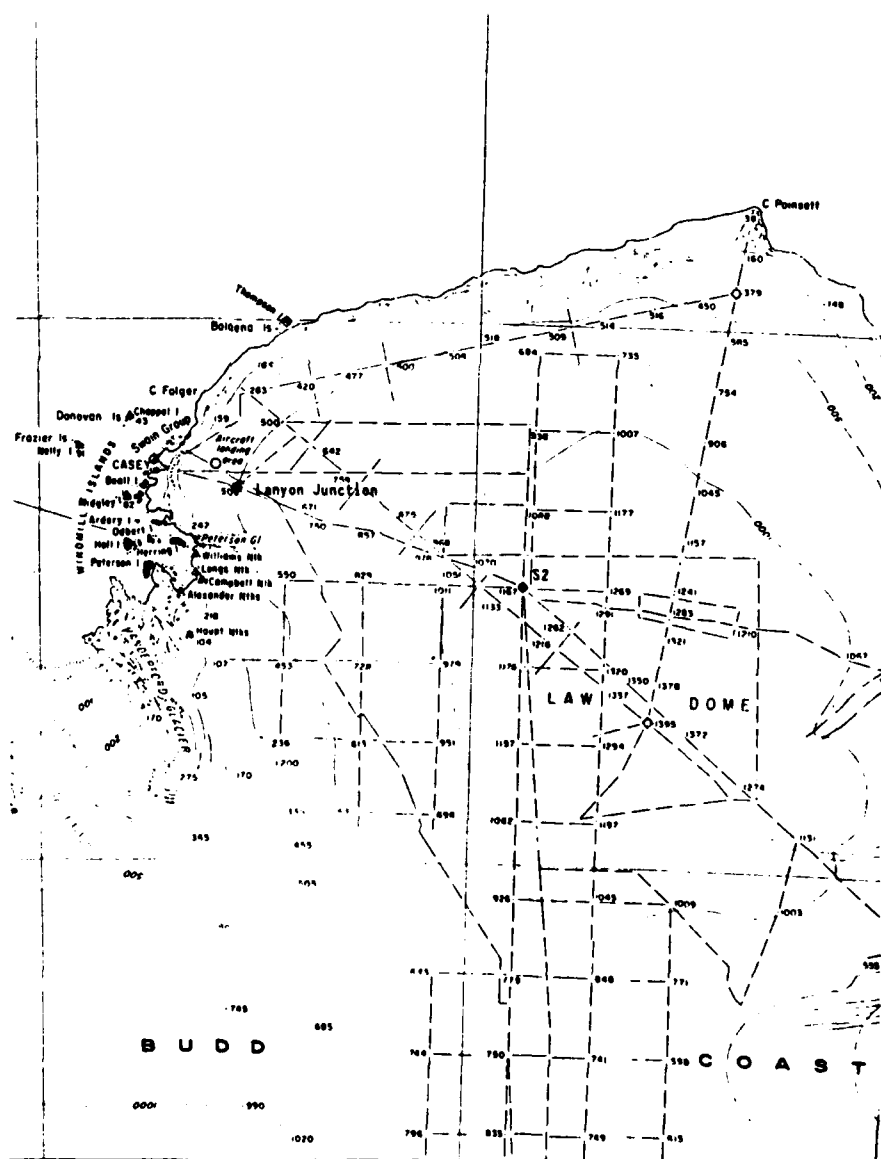


Figure A1. Map of Casey and Law Dome area.

\*Modified slightly from a report published by the Melbourne University Programme in Antarctic Studies (Report No. 64, May 1984) written by D.S. Russell-Head, W.F. Budd and P.J. Moore.

Drum beacon

East

Snow pole  
GW01

0 100 m

Runway site

a. Lanyon Junction Station and Lanyon Junction (7 February 1984).

b. Location of runway site (4 February 1984).



c. Test strips and trial pavement (4 February 1984).

runway

Lanyon Station

d. Lanyon Station and runway site (7 February 1984).

Figure A2. Aerial views of runway site.

## BACKGROUND

The testing program described in this appendix was part of the Casey runway trials activities at Lanyon Junction during the 1983–84 summer. The overall objective of the trials program was to assess the practicability of constructing a compressed snow pavement that would support C-130 wheel loads. The main construction equipment included a D7 Caterpillar tractor, a Schmidt snow miller, a 14G Caterpillar grader, two pneumatic-tired rollers (a Rollpac 21 and the equivalent of a Rollpac 38) and a disk plow.

### Snow testing program

The major aim of the snow testing program was to define the design parameters of a compressed snow runway at the Lanyon Junction site. To that end, measurements were to be made of snow density, rammsonde hardness, California Bearing Ratio (CBR), plate bearing load-deflection behavior, and constant-load creep behavior.

The results from these tests were to be analyzed for relationships between the snow test parameters and pavement performance. A correlation between pavement bearing capacity and some easy method of in situ measurement was of particular interest. The efficacy of the construction equipment and the results of proof rolling were also to be recorded and analyzed, in association with the Airfield Project Engineer.

As a consequence of the 1983–84 field testing program, data collected at the site are tabulated in Russell-Head et al. (1984), and the methods for snow runway testing are documented in Appendix B. This appendix describes the methods and equipment used to collect the data, presents the data in graphical form, analyzes the main features of the data, and provides the relationships between various parameters.

Agencies responsible for other activities at Lanyon Junction will have separate reports that will be useful additional references. The Australian Survey Office provided the survey control, the Airfield Project Engineer was from the Department of Housing and Construction, and the Bureau of Meteorology mounted a test flight forecasting program, which included the collection of meteorological data at Lanyon Junction.

### Casey runway site

Lanyon Junction had been nominated as the site for a compressed snow runway to

serve Casey (Russell-Head et al. 1982). The main reasons for its selection were

- Lanyon Junction is about the closest site to Casey that offers a positive net annual accumulation of snow;
- The Lanyon Junction site is free of extensive melting; and
- The average direction of strong winds is from the east and Lanyon Junction offers an east–west runway siting with minimal side slope.

Russell-Head et al. (1982) give estimates of meteorological and glaciological parameters for Lanyon Junction. The mean elevation of the runway site is about 500 m, and the average daily temperature in December is estimated to be about  $-3^{\circ}\text{C}$ , rising to about  $-1^{\circ}\text{C}$  in January. The average daily temperature variation is about  $7^{\circ}\text{C}$ . The annual accumulation averages  $0.1 \text{ Mg m}^{-2}$ . The surface slope is about 1.5%, and the horizontal surface movement is less than 10 m per year.

Figure A1 shows the general Casey and Law Dome area. Figure A2 shows the relationship between Lanyon Junction, the station, the test strips and the runway site. Figure A3 shows the layout of the Lanyon Junction test site in 1983–84.

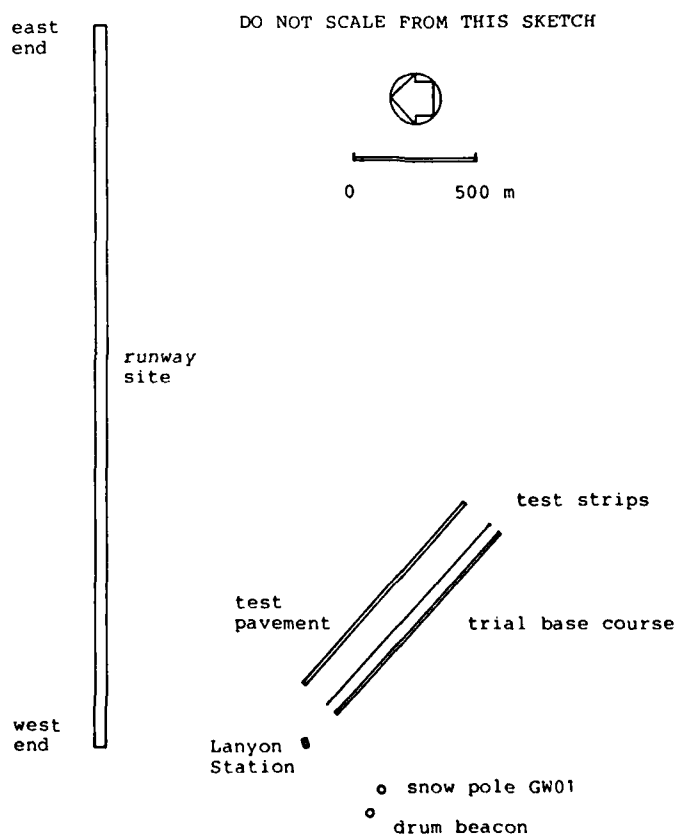


Figure A3. Map of Lanyon Junction area.



## TESTING AND RECORDING EQUIPMENT

This section describes the equipment used to obtain the data in the field. The data are discussed in the next section.

### Density measurement

Samples for density measurement were gathered in a number of ways:

- Core cutting by impact hammer;
- ico hand corer;
- Egon Wherle's electro-mechanical drill;
- Hand saw; and
- CBR corer.

Two types of balances were used to measure the mass of the samples:

- Digital Mettler balance (4.2 kg capacity, 0.1 g sensitivity) and
- Ohaus triple beam balance (2.6 kg capacity, 1 g sensitivity).

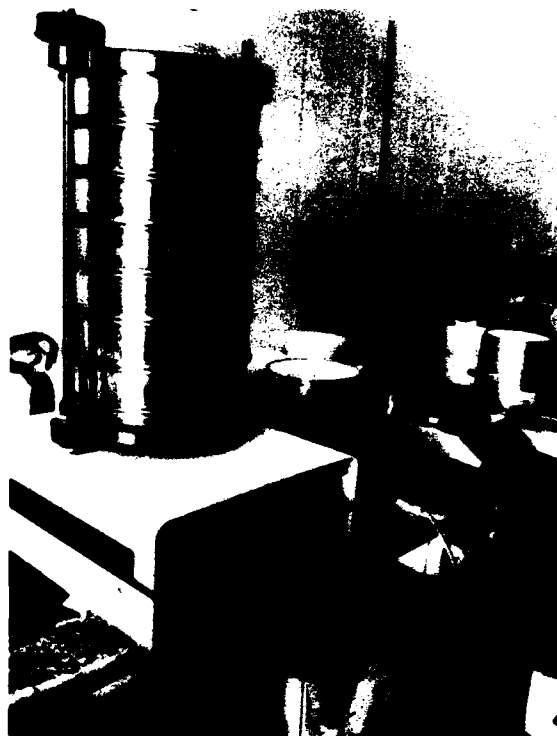
The impact hammer for the core cutting had a drop mass of 4.5 kg and a drop height of 87 cm. The core cutters were cylindrical steel tubes of 99.8 mm internal diameter, 121.5 mm long with an internal volume of 950 cm<sup>3</sup>. This system worked reasonably well on medium-density snow but for higher-density snow (greater than about 0.6 Mg m<sup>-3</sup>) the samples were badly fractured.

The other sampling methods worked well, and a hand saw was then used to trim the snow into volumes for mass measurement. The mass-sample dimensions were measured with a vernier caliper (read to 0.1 mm). The mechanical balance was used away from the station, and the digital balance was used mostly in the cold laboratory. Both balances performed well in the cold conditions.

Errors in the density determination arise mostly from the volume measurement (up to 3%). The error in the mass measurement is less than 0.25%. The sample itself may not be a true average representation of the material sampled, and this sampling error is probably larger than the error of density determination.

### Particle size distribution

The particle size distribution of disaggregated snow was obtained by sieving a sample through a set of 10 wire-mesh sieves with openings ranging from 0.075 to 6.7 mm. Snow samples were placed in the top of the sieve set in a mechanical shaker in the cold laboratory (Fig. A4) and shaken for 10–15 minutes. The masses retained by each sieve were measured with the digital Mettler balance (0.1 g sensitivity).



*Figure A4. Cold laboratory in freezer van showing sieve shaker (left), CBR molds and digital balance.*

The Schmidt processed snow was sieved immediately after production. Samples of in situ snow were disaggregated by crushing with gloved hands and rubbing the firm snow against itself to dislodge the individual snow grains.

The equipment performed quite well, except that the shaker (Endercotts Model EVS1) did not work on its intermittent cycle.

### Penetrometers

Two types of penetrometer were used. First, the rammsonde of Swiss origin has a long history of use in glaciology. The drop masses of the rammsonde are generally 1 kg and 3 kg. The maximum drop height is 50 cm. The conical tip has an included angle of 60° and a maximum diameter of 40 mm.

The other penetrometer is of soils testing origin and is available commercially as the "Scala penetrometer." This instrument is more robust than the light-weight rammsonde. The drop mass is 9 kg and the maximum drop height is 50.8 cm. Different tips can be fitted to the threaded end of the first rod. Three tips were specially made from hard stainless steel with the same conical geometry as the rammsonde. The tip diameters were 20 mm, 40 mm (same as rammsonde) and 80 mm. The purpose of

these tips was to test hard snow (with the 20-mm tip) and low-density snow (with the 40-mm tip). Drop penetrometers are very simple instruments, and there were no problems in their use in the field.

#### California Bearing Ratio testing

Both field and laboratory tests were performed. The field test system comprised a motorized jack fitted to a cantilever beam attached to the rear of a D5 Caterpillar tractor. A load cell was placed between the CBR piston and the jack, which allowed the electronic recording of the piston load with time.

This field CBR test system worked well mechanically and electronically, but the test was invalidated by the slow melting of the piston into the test snow surface. The problem could not be easily overcome, and only two field tests were performed. The remaining 15 tests were performed on cored in situ samples which were placed in a CBR test machine (ELE Model EL29-001) in the cold laboratory (Fig. A5).

The load recording system consisted of a 50-kN load cell (Interface Model 1210-BF), a programmable digital voltmeter (Hewlett Packard Model 3468B), a calculator-controller (HP 41CV), a printer-plotter (HP 82143A) and a digital cassette

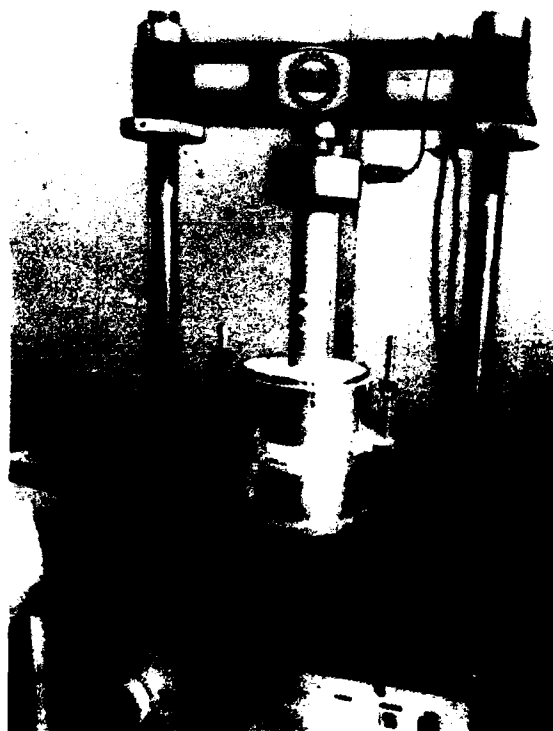


Figure A5. California bearing ratio testing machine in the cold laboratory. The piston load is measure with the load cell.



Figure A6. CBR load cell instrumentation for logging piston load with time. This equipment was housed in the site office.

recorder (HP 82161A). Only the load cell was in the cold laboratory; the rest of the data acquisition system was in the site office (Fig. A6).

The piston speed was 1 mm per minute, and the load was measured every 6 seconds, i.e. every 0.1 mm of piston travel. The load was displayed in graphical form by the printer-plotter during the 15-minute test period, and the actual load values at each 0.1-mm interval were recorded at the completion of the test as digital values by the cassette recorder.

The gearbox in the test machine needed to be warmed before the drive system would run. Apart from that problem, the laboratory CBR system worked very well.

#### Plate bearing test

A circular plate, 600 mm in diameter, was made from 10-mm-thick mild steel reinforced with six radial ribs, 10 x 50 mm. The plate was loaded with the smaller roller (Rollpac21 weighing 16.2 Mg) via a hydraulic jack (Fig. A7). The plate displacement was measured with a resistance displacement transducer (Pye-Ether PD20). This sensor was mounted on a 4-m-long steel beam, weighed down at each end on blocks of polystyrene resting on the pavement. Because the plate was under the roller and always in the shade, there was no melting of the pavement snow by the plate during the test.

The data recording system was the same as that used for the CBR tests. The plate movement was



Figure A7. Unladen Rollpac 21 roller balanced as a dead weight on a hydraulic jack on the plate. The settlement logging equipment is in front of the roller.

displayed and recorded every 15 seconds. The only difficulty in setting up the system was the placement of the hydraulic jack to balance the roller.

#### Meteorological and glaciological recording

An automatic data acquisition system was used to record air temperature, snow temperatures, incident radiation, wind speed and wind direction at 15-minute intervals. The various sensors were connected to a Hewlett-Packard 3421A data acquisition and control unit, and this was in turn controlled by an HP 85B computer via the HP-IB (IEEE-488) bus. A specially written program for the HP 85B initiated a sensor scan every 15 minutes, converted the sensor values to physical units, and formatted and recorded the data on cassette tape in the HP 85B. The data were also transmitted every 15 minutes via the GP-IB to an Epson MX-80 printer (Fig. A8).

The data acquisition and recording system worked well after software debugging. There were some difficulties with the 3421A due to static charge build-up on the sensor lines during blizzard condi-



Figure A8. Automatic data acquisition and recording equipment in the station site office.

tions, but this problem was solved by grounding appropriate sensor terminals. Some data were also lost due to 240-V power loss. Apart from these two problems ancillary to the system, the data recording equipment functioned without fault.

The positions of the various sensors are indicated in Figure A9. The data acquisition system shown in Figure A8 was housed in the site office; the layout of the snow and meteorological sensors is shown in Figure A10.

#### Air temperature

The air temperature was monitored in a small screen clamped to a snow pole so that the sensor was 0.5 m above the snow surface. The position of the screen was changed during the summer period. From 19 to 26 January the screen was positioned to the south of the site office, and from 26 January to 8 February the screen was to the east of the building line (Fig. A9 and A10).

The sensor was a platinum element resistor (Degussa Type W 60/1). Its resistance in a freezing-point bath was measured before installation in the screen (Fig. A11), and the computer program performed the conversion from resistance to temperature by solving the following quadratic equation:

$$R_t = R_0 (At^2 + Bt + 1) \quad (A1)$$

where  $R_t$  = resistance at  $t^\circ\text{C}$  (ohms)  
 $R_0$  = resistance at  $0^\circ\text{C}$  (ohms)  
 $t$  = sensor temperature ( $^\circ\text{C}$ )  
 $A = -0.57841 \times 10^{-6}$   
 $B = 0.39078 \times 10^{-2}$

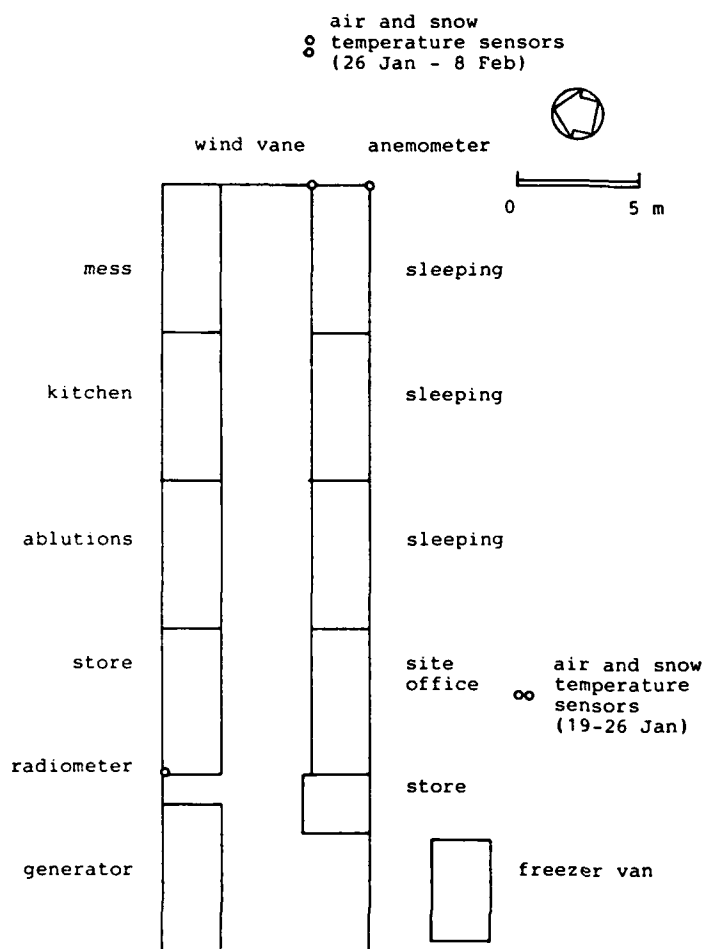


Figure A9. Plan of the Lanyon Station area showing the positions of meteorological and snow temperature sensors.

As the screen is not a perfect radiation reflector, its internal temperature was probably higher than the ambient air temperature during calm days. Also on near-calm days when the screen was downwind of the station, higher than true ambient temperatures were experienced within the screen.

This effect was particularly noticeable when the screen was to the east of the site office. On warm, calm days, the screen could be bathed in warm air from the heated station structure. When there was a slight west-southwest breeze, the generator exhaust (which was discharged to the rear and below the buildings) could drift over the screen. These factors should be borne in mind when attempting to interpret the air temperature record.

#### Snow temperature

Platinum element resistors (Degussa Type W 60/1) were used to monitor in situ snow temperatures. The sensors were placed in the wall of a backfilled trench to the south of the site office from 19 to 26 January. These were moved to a new site

upwind of the station after it became clear that the snow around the trench had been contaminated with ash and soot from a fire (used to burn packing timber). Excessive melting had occurred in the snow due to the increased absorption of radiation by the dark soot. The meltwater had probably dissolved some of the ash, and this would have depressed its refreezing temperature. The snow temperature data need to be interpreted with these effects in mind.

After 26 January the sensors were attached to a cane rod with white insulation tape (Fig. A12). The assembly was fitted into a hole bored with a Pico hand corer and then back-filled. The sensors were placed at 0.1, 0.2, 0.5 and 1.0 m below the snow surface. After a day or so the sensors should have reached equilibrium with the ambient snow, and the temperatures recorded in the new arrangement should accurately reflect the general temperature regime in the surface snow.

#### Solar radiation

The incident solar radiation was measured with a Kipp and Zohnen type of radiometer (Fig. A13). The sensor was mounted on the outer corner of the station store (Fig. A9).

The voltage output was measured with the high-impedance (1010 ohms) voltmeter within the HP 3421A. The calibration of this

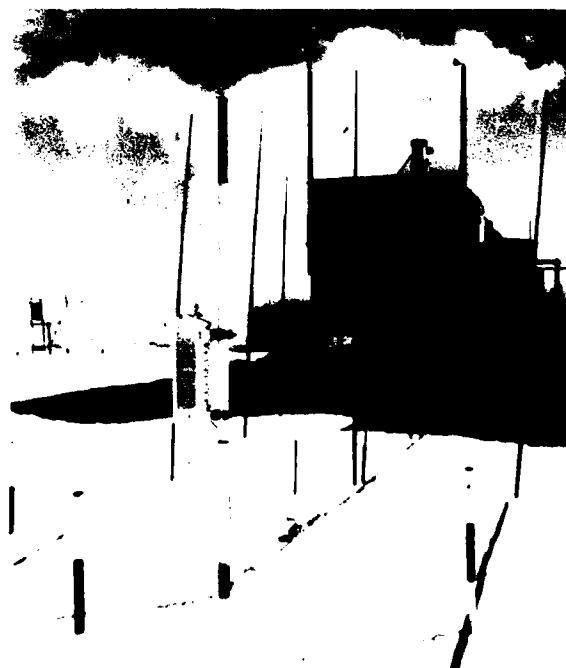


Figure A10. Layout of air and snow temperature sensors, cup anemometer and wind vane.

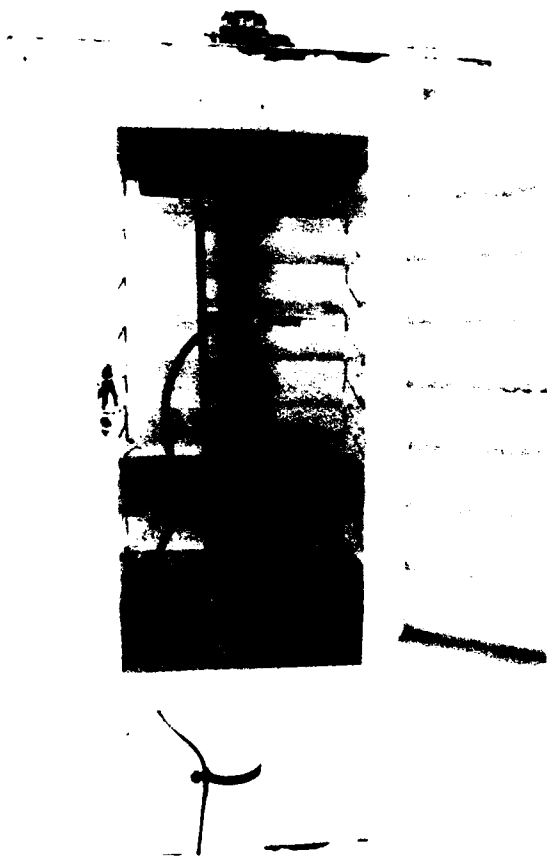


Figure A11. Platinum-resistance temperature sensor housed in the small screen together with a mercury-in-glass thermometer.



Figure A12. Snow temperature sensors taped to a cane rod before insertion in a hole drilled by a hand corer (28 January 1984).



Figure A13. Incident radiation sensor mounted on top of station store module.

sensor is not known. The voltage output is a linear function of radiation absorbed by the radiometer. A horizontal screen is normally fitted to this type of instrument, and some errors may occur with the installation as shown in Figure A8, especially when the sun is in a subhorizontal position.

The purpose of including this instrument in the sensor set was to provide some record of the sunniness and cloudiness of each day, rather than to make accurate quantitative records of the net incident radiation. The millivolt readings should be viewed then as an indicative record of the general cloud state during the period.

An absolute calibration scale can be estimated from previous detailed radiation studies in Antarctic latitudes (e.g. Weller 1967). Peak (noon) clear-day global radiation during January can be expected to be about  $0.84 \text{ kW m}^{-2}$  in the Casey-Law Dome region ( $1 \text{ cal cm}^{-2} \text{ min}^{-1} = 697.8 \text{ W m}^{-2}$ ).

#### Wind speed

A cup anemometer (Rimco Type R/CGA) was used to measure wind speed. It was mounted on a pole at the leading edge of the building line (Fig. A10). The height above the snow surface was about 6 m.

The cup shaft was coupled to a small DC generator, and its open circuit output voltage was sensed. The conversion to a wind speed value was incorporated in the computer program:

$$S = 137.5 V + 0.8 \quad (A2)$$

where  $S$  is the wind speed (knots) and  $V$  is the output voltage (V).

Equation A2 is derived from the manufacturer's data and implies that winds below 0.8 knots will not rotate the cup shaft. Therefore, wind speeds below this stall speed will still be recorded as 0.8 knots. The instrument appeared to have more rotational friction and noisier bearings after the recording period than at the start, so the stall speed may have progressively increased during its period of use.

#### Wind direction

A wind vane was mounted on a pole at the leading edge of the building line (Fig. A10), and its height above the snow surface was about 6 m. The vane shaft was connected to a rotating potentiometer whose zero position was oriented due north. The

resistance of one section of the potentiometer was measured with the HP 3421A and converted to a true bearing with the formula

$$D = R/1.26 \quad (A3)$$

where  $D$  is the true bearing ( $^{\circ}$ ) and  $R$  is the resistance (ohms)

There is a segment at the ends of the circular potentiometer where the wiper is out of contact. The output for this section is variable and is usually denoted in the record by a period or a negative value. The orientation of the vane for these outputs is between 355 and  $0^{\circ}$  true.

The wind speed and direction values are essentially spot values, not averages. The wind speeds recorded are not necessarily maxima.

#### TEST DATA

This section presents the data collected at the Lanyon Station site, mostly in graphical form. The original data are tabulated in Russell-Head et al. (1984).



*a. Three-meter-deep trench dug by the Schmidt snow miller.*



*b. Side of trench showing ice lenses alternating with firn snow. The ice lenses are typically a couple of centimeters thick with 5-10 cm of snow between lenses.*

**Figure A14. Snow test pit near Lanyon Station.**

## Overview

The data are presented in the sequence of snow structure, snow strength and pavement proof test. The records of meteorological and snow temperature conditions are also discussed.

### *In situ conditions*

The structure and strength of the in situ snow has an important influence on the thickness of pavement required to support a given wheel load. Most of the data collected on site have arisen from the investigations of the in situ snow.

An unexpected snow structure was revealed when trenches were dug into the snow. Earlier investigations (Cameron et al. 1959) were either at higher altitudes (where there was a single annual layer of refrozen meltwater) or at lower altitudes (where there was essentially blue ice). At the Lanyon Junction site, there were multiple annual melt zones alternating with firn snow (Fig. A14). This structure of the subgrade snow has a much higher strength than the typical  $0.35\text{ Mg m}^{-3}$  snow that had been conservatively expected. The snow-ice structure provides an excellent source of primary material for processing by the snow miller.

### *Snow processing and pavement production*

The strength of snow depends strongly on its density. The main purpose of working the in situ material was to increase the density. Methods were developed with the construction equipment to produce a densified snow pavement for snow that was either cold or moist.

For moist snow the simplest way of starting the pavement production was to drag a heavily laden plate over the moist snow. In cold snow the drag method of compaction did not work, and the best method appeared to be track rolling, i.e. repeated passes of laden tracked vehicles. The track-rolled snow needed some time to age-harden. The base course produced by either method allowed the compacting and grading equipment to operate with a significantly reduced chance of bogging.

The pavement snow is produced by disaggregating the in situ snow and ice with the snow miller. The processed snow has an extended range of particle sizes and is denser than the surface snow. The grader levels the processed snow, which is then compressed to a higher density by the pneumatic-tired rollers.

### **Snow stratigraphy**

Two cores for stratigraphy analysis were obtained with Egon Wherle's electromechanical drill at a site some 15 m from the northwestern corner of

the station (Fig. A15). Figure A16 shows the ice layering in the cores and also the densities of a number of sections from the cores. Clear bubbly ice alternated with firn snow throughout the cores, and the transition between the two forms of ice was sharp.

The density of the ice was about  $0.8\text{ Mg m}^{-3}$  and the density of the snow between the lenses averaged about  $0.43\text{ Mg m}^{-3}$ . The total thickness of the ice lensing in the first core of 1500 mm was about 235 mm, and in the second core of 2500 mm, 293 mm was ice. The average ice lens thickness was about 16 mm.

For an assumed dichotomy of snow and ice, the average density of the material can be calculated from the proportions of ice to snow. The average proportion (by volume) of ice is about 16%, which gives an average density of about  $0.48\text{ Mg m}^{-3}$ . The average annual accumulation at the site is about  $0.1\text{ Mg m}^{-2}$  and this corresponds to an annual burial rate of 0.21 m.

### **Particle size distributions**

Samples of snow from core 2 were disaggregated and sieved. The cumulative particle size

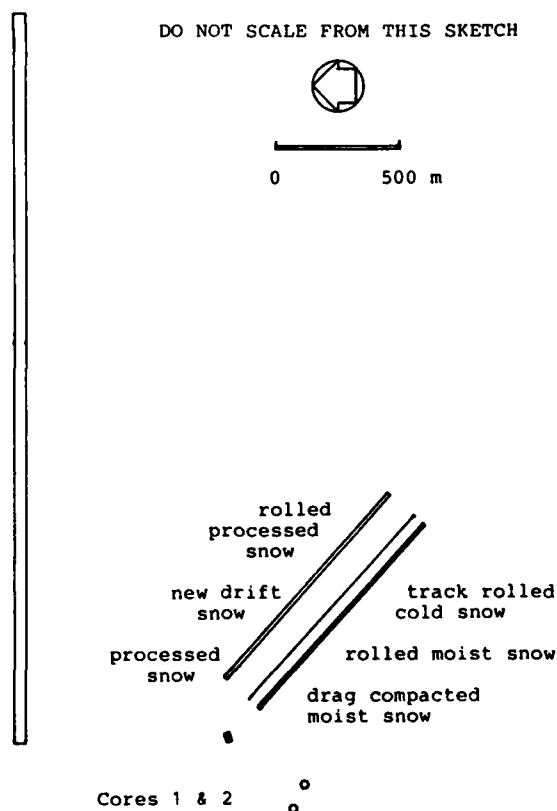
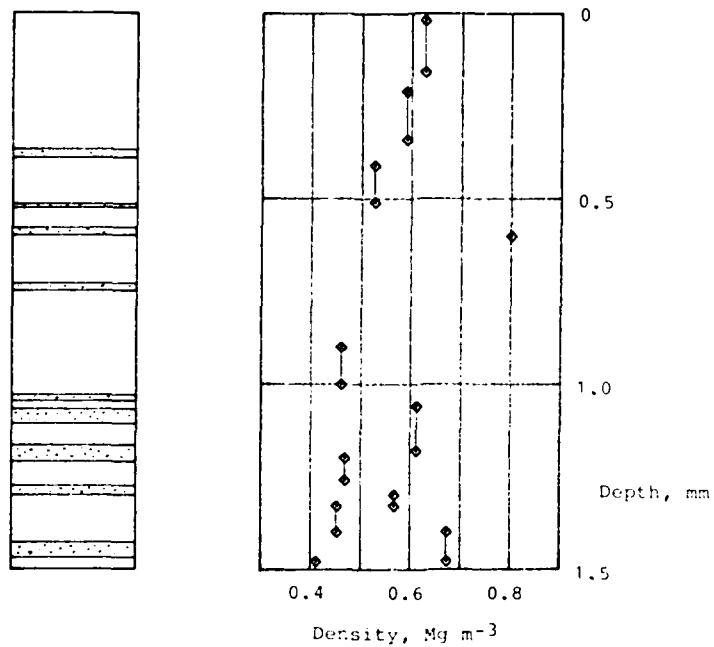
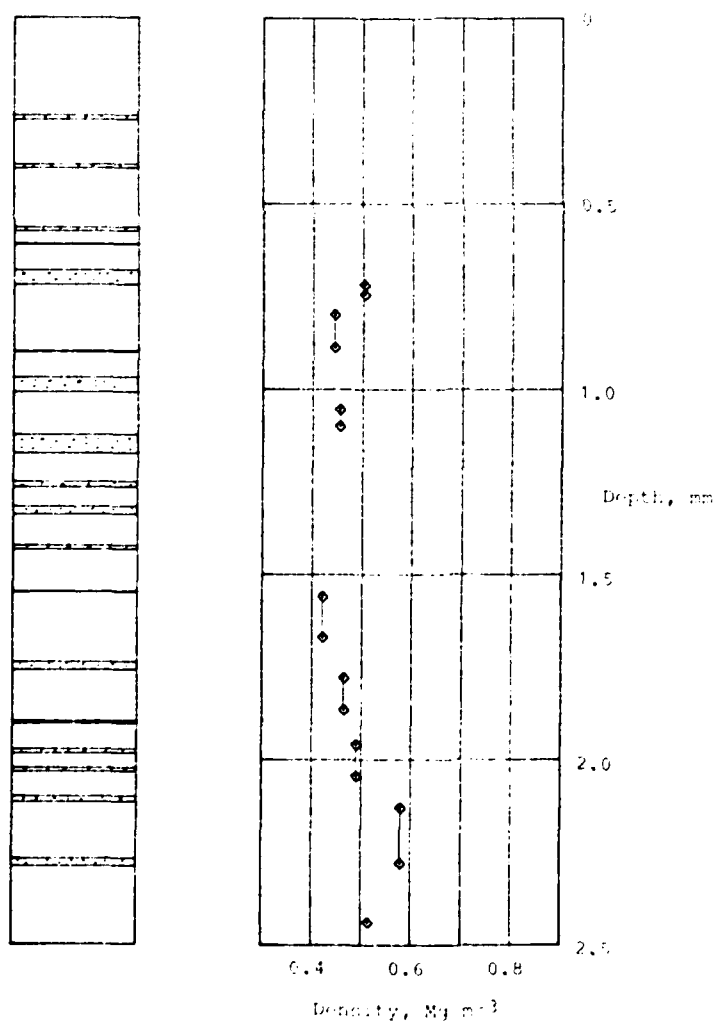


Figure A15. Map of test area showing positions of samples taken for snow stratigraphy, density and particle size distribution.



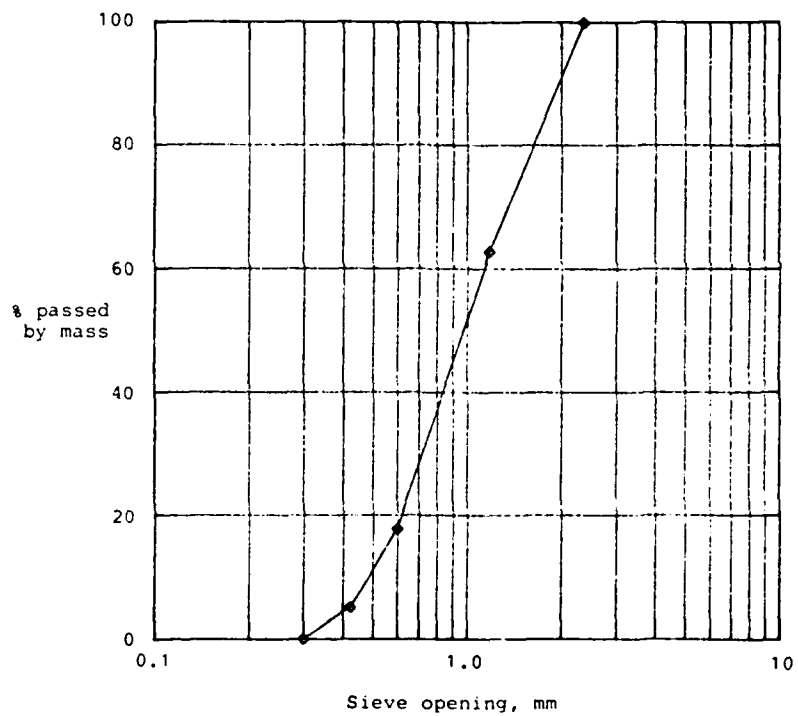
a. Core 1.



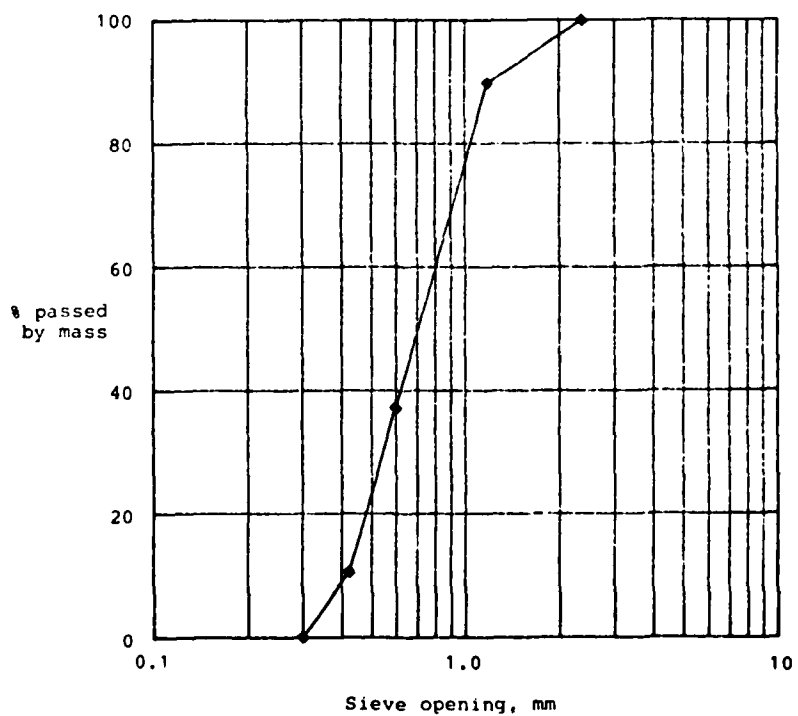
b. Core 2.

Figure A16. Ice layering and snow densities at Lanyon Station site.



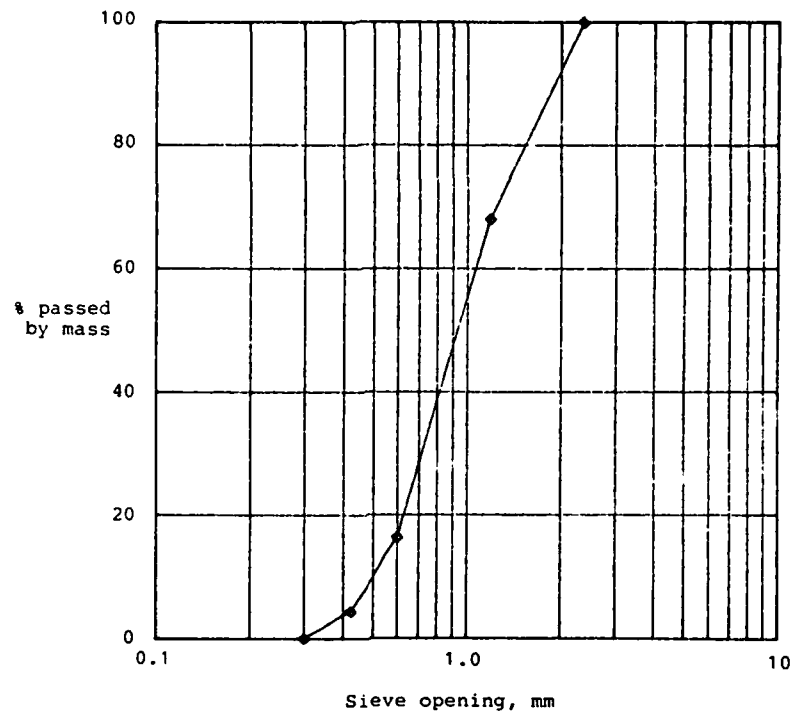


*a. 720 mm below the surface.*

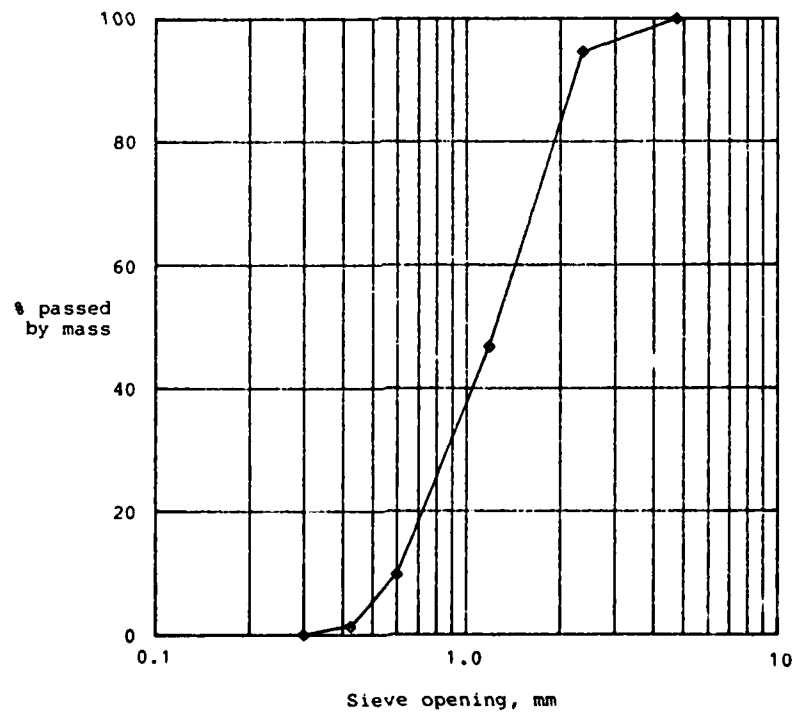


*b. 800 mm below the surface.*

**Figure A17. Particle size distributions of disaggregated snow.**

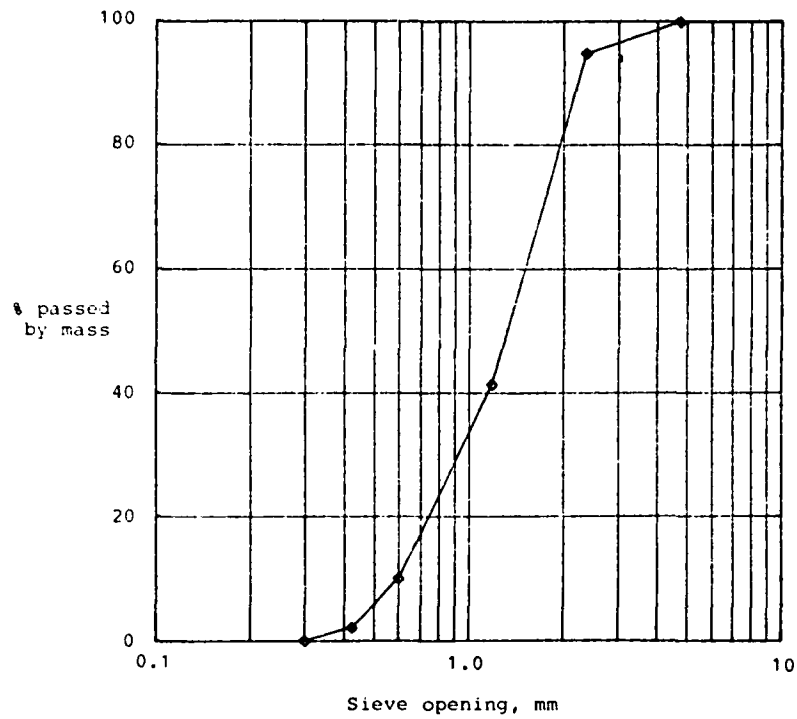


*c. 1100 mm below the surface.*

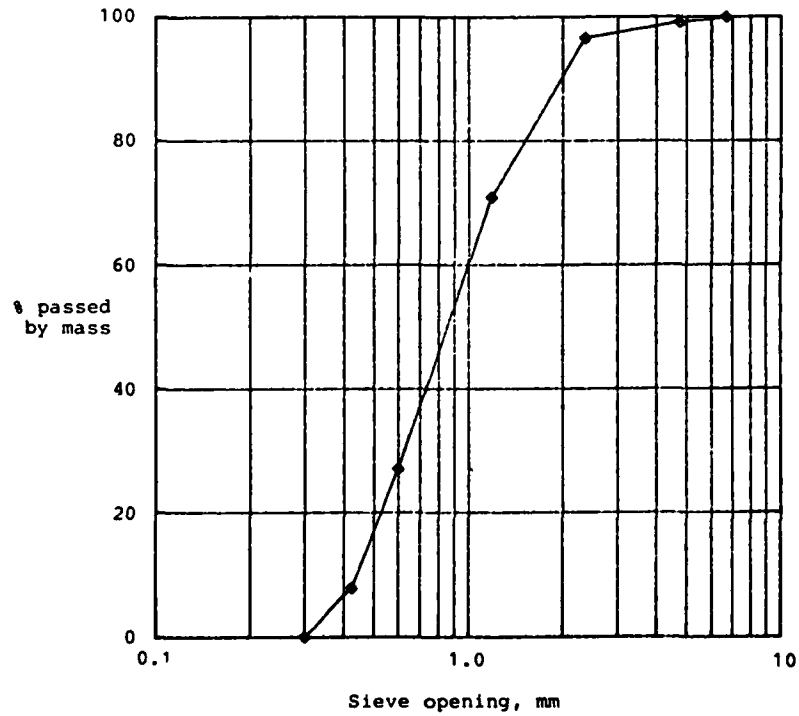


*d. 1600 mm below the surface.*

*Figure A17 (cont'd).*

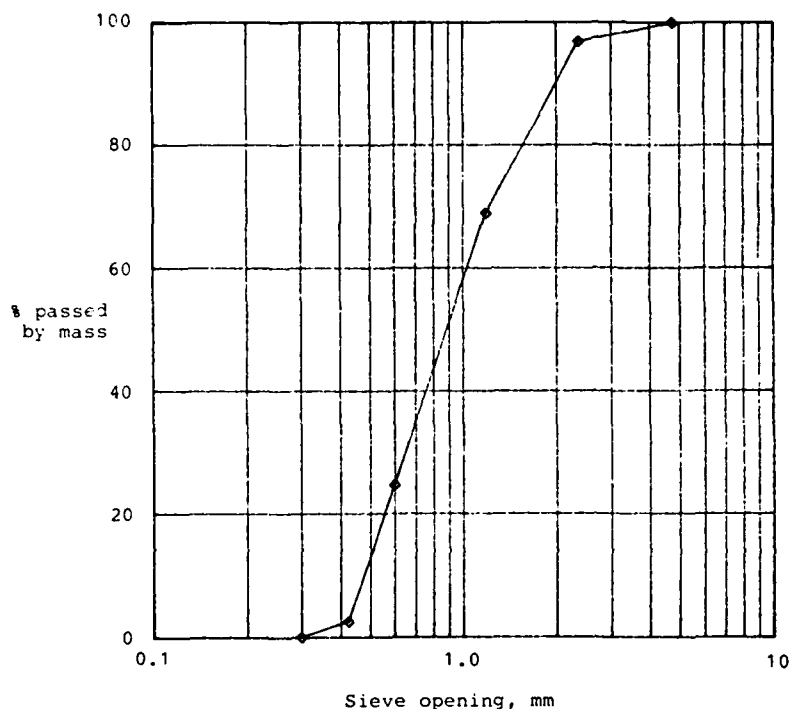


*e. 1800 mm below the surface.*



*f. 2200 mm below the surface.*

**Figure A17 (cont'd). Particle size distributions of disaggregated snow.**



g. 2500 mm below the surface.

Figure A17 (cont'd). Particle size distributions of disaggregated snow.

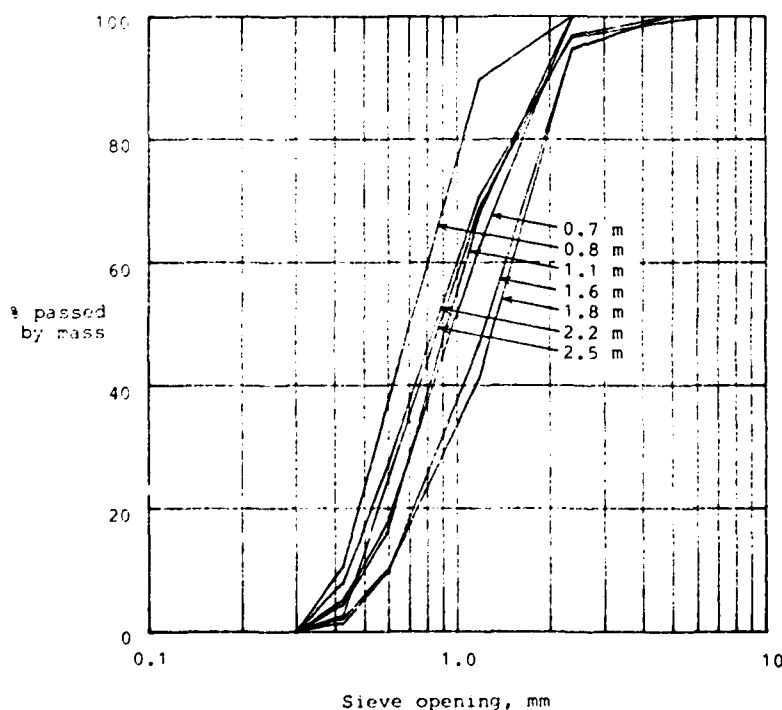


Figure A18. Particle size distribution of all samples of disaggregated snow from Core 2.

Table A1. Typical densities of various types of snow at Lanyon Station site.

| Type of snow                  | Density ( $\text{Mg m}^{-3}$ ) |
|-------------------------------|--------------------------------|
| <i>In situ</i>                |                                |
| New drift snow                | 0.42                           |
| Snow between ice lenses       | 0.45                           |
| Ice lenses                    | 0.8                            |
| Average in situ snow and ice  | 0.48                           |
| <i>Processed</i>              |                                |
| Track-rolled cold snow        | 0.6                            |
| Drag-compacted moist snow     | 0.6                            |
| Rolled moist snow             | 0.7                            |
| Fresh processed snow (29 Jan) | 0.63                           |
| Fresh processed snow (7 Feb)  | 0.59                           |
| Rolled processed snow         | 0.65                           |

distributions are shown in Figure A17. Distributions for all the samples are shown on the plot in Figure A18. The average particle size appears to cycle with depth, within the 0.7- to 1.4-mm range.

The particle size distribution of new drift snow shows a much smaller mean grain size of about 0.47 mm (Fig. A19). The range of grain sizes is quite narrow. The snow processed by the Schmidt snow miller exhibited a wide range of grain sizes from 0.3 to greater than 10 mm (Fig. A20). The mean grain size was about 1.5 mm.

#### Snow densities

Table A1 lists typical densities of in situ and processed snow at the Lanyon Junction site.

#### Penetrometer data

The sites of the penetrometer tests are shown in Figure A15. The profiles are shown in Figure A21. The penetrometer numbers in the figures are from the tables in Russell-Head (1984). They had been calculated with the formula

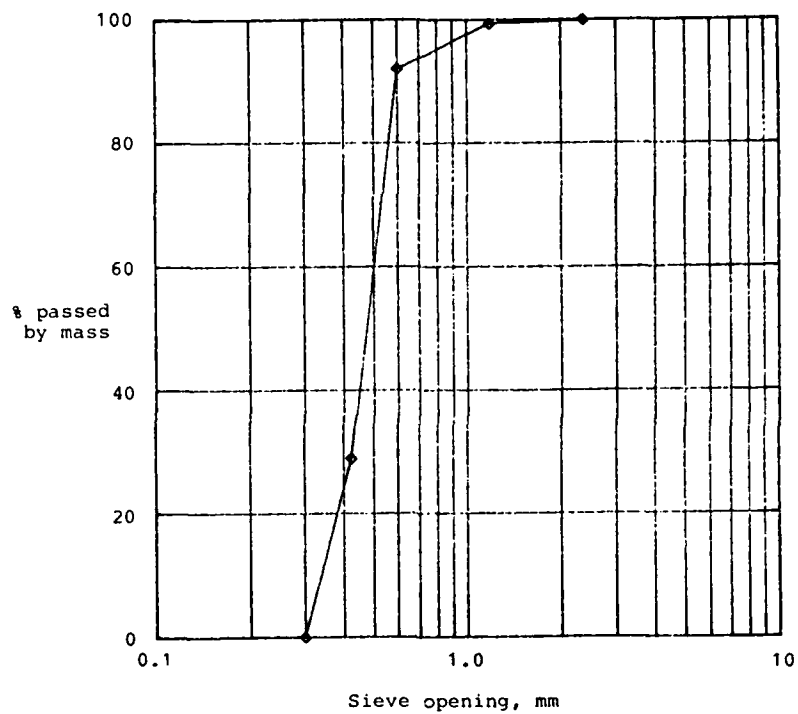
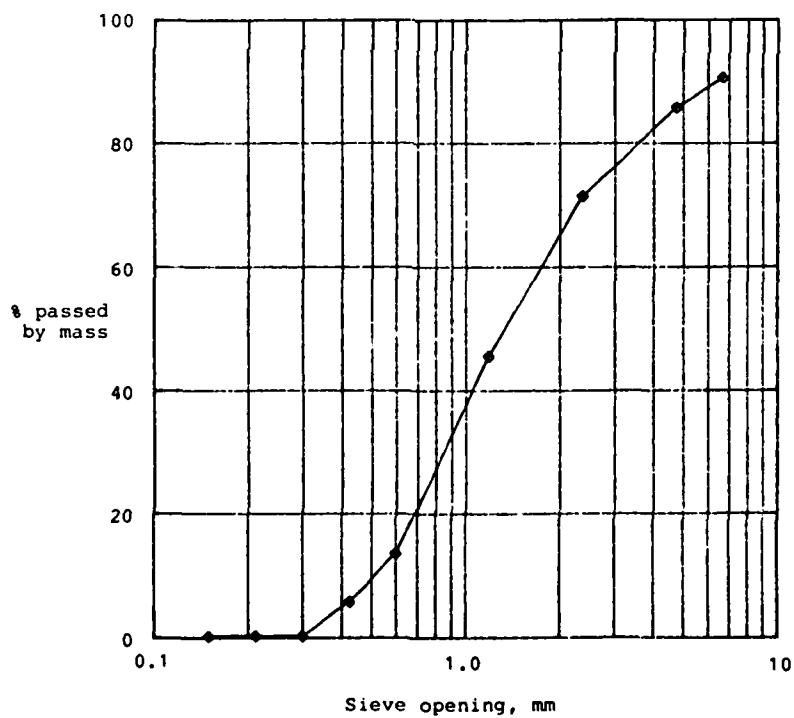
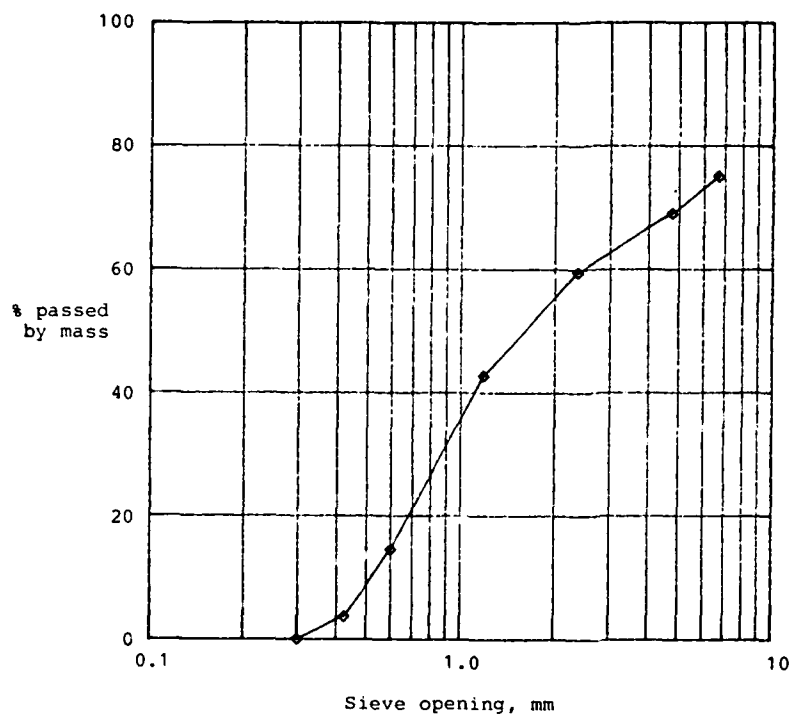


Figure A19. Particle size distribution of new drift snow.



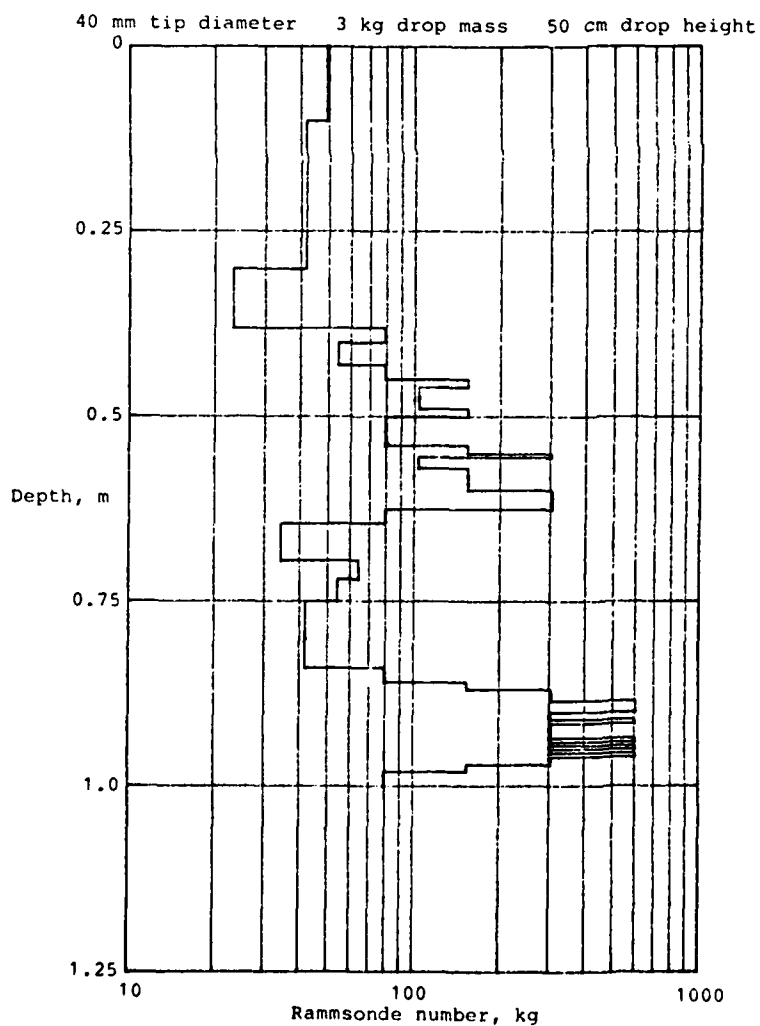
a. 29 January 1984.

Figure A20. Particle size distribution of Schmidt processed snow.



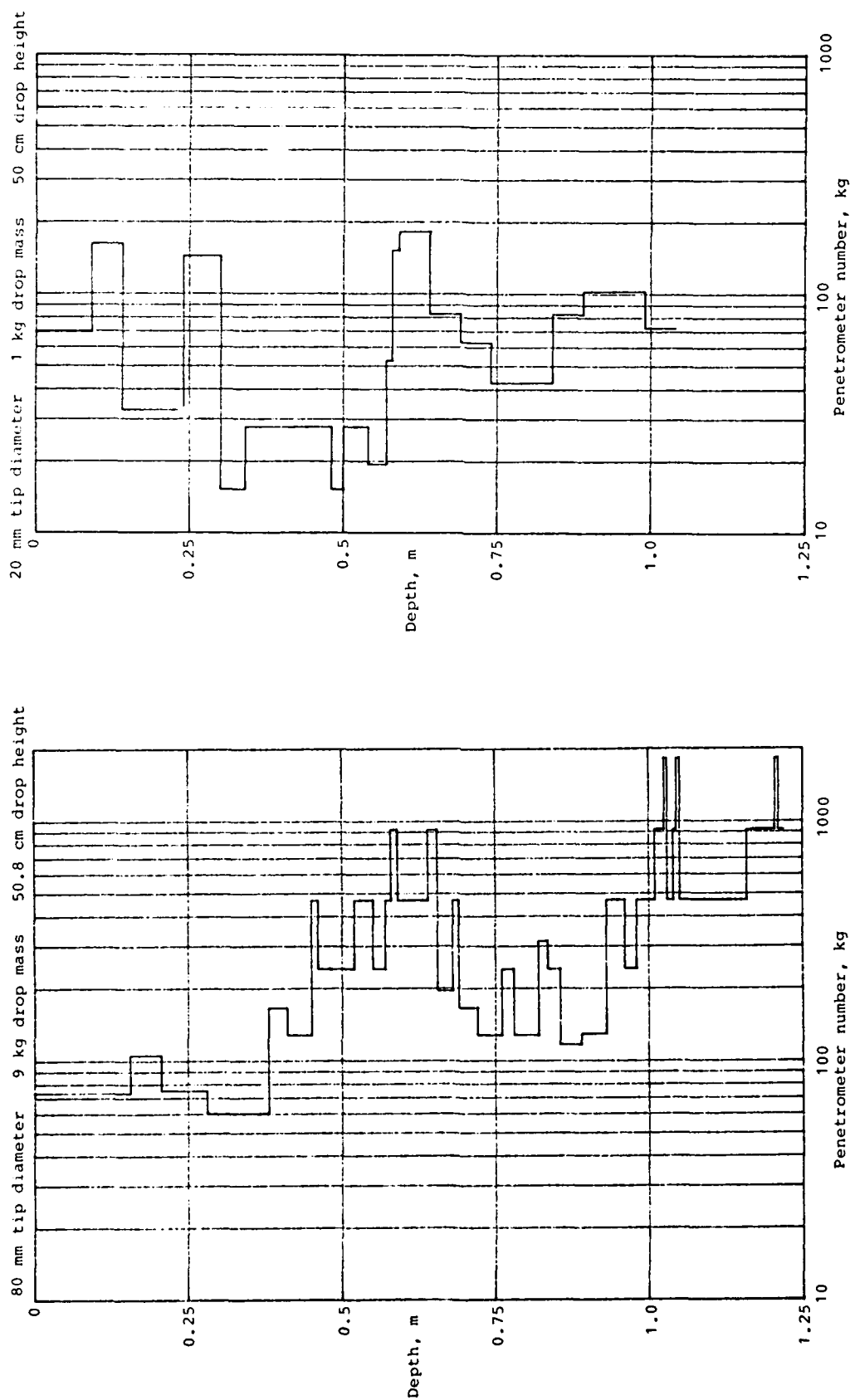
*b. 7 February 1984.*

*Figure A20 (cont'd). Particle size distribution of Schmidt processed snow.*



*a. Western end of runway site; 400-mm tip diameter; 3-kg drop mass; 50-cm drop height; 25 January 1984.*

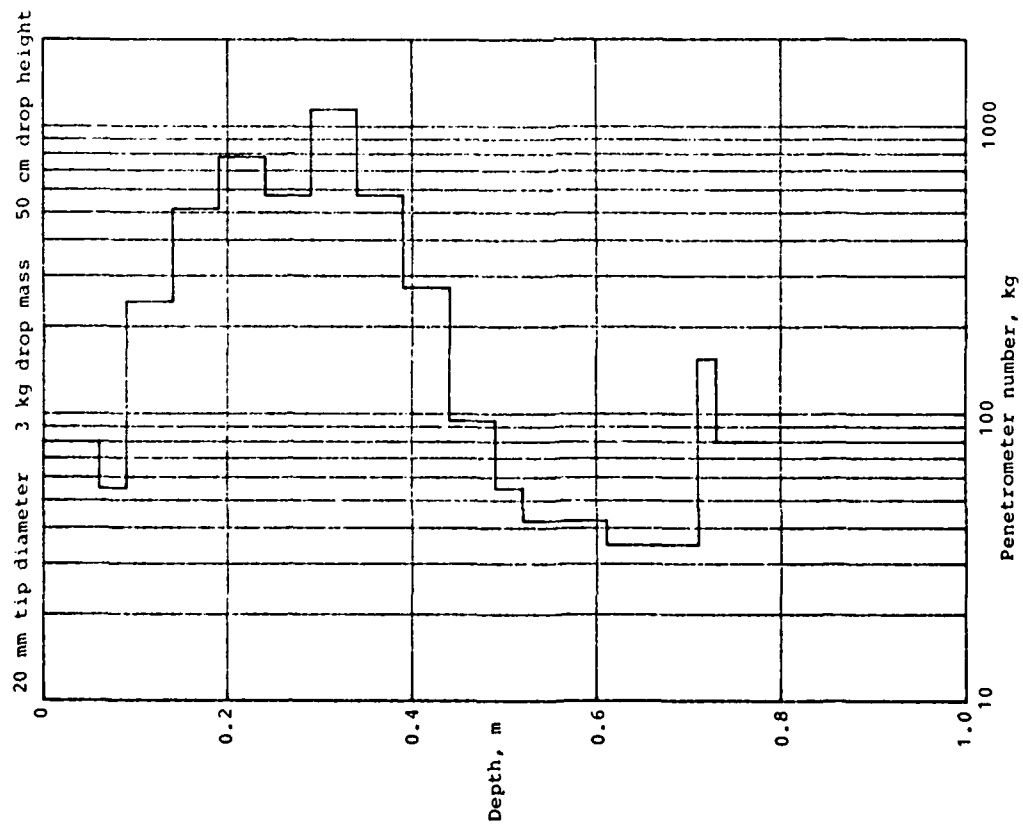
*Figure A21. Rammsonde profiles.*



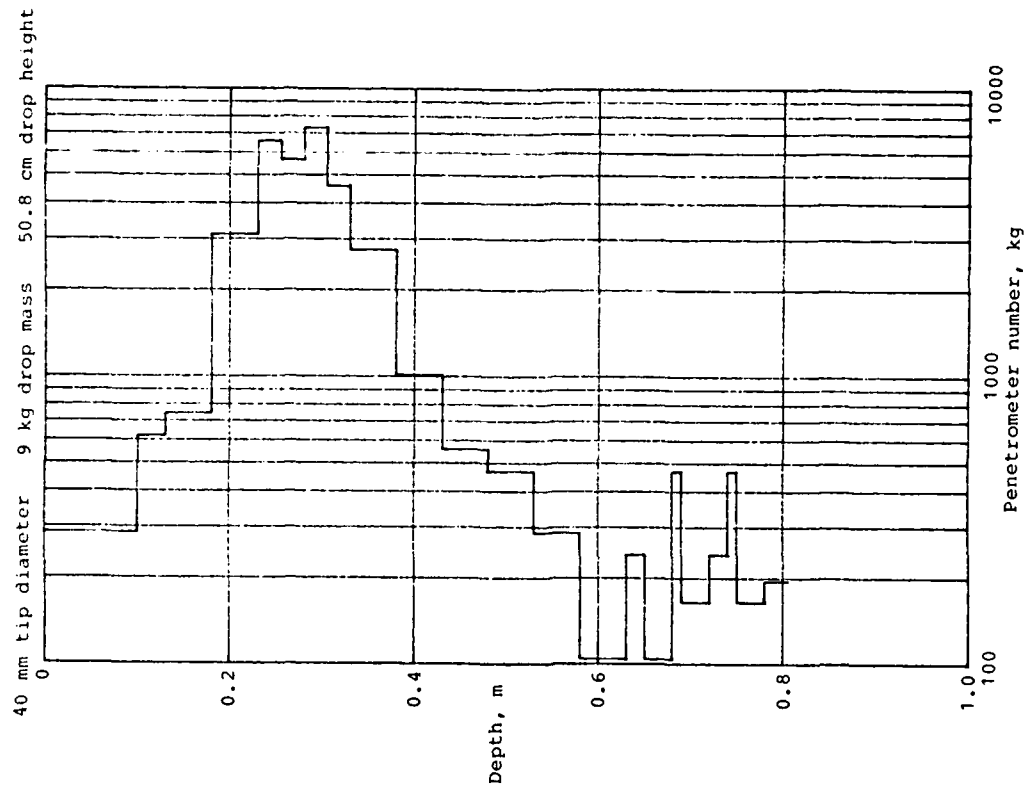
b. Western end of runway site; 80-mm tip diameter; 9-kg drop mass; 50.8-cm drop height; 25 January 1984.

c. Western end of runway site; 20-mm tip diameter; 1-kg drop mass; 50-cm drop height; 25 January 1984.

Figure A21 (cont'd). Rammsonde profiles.



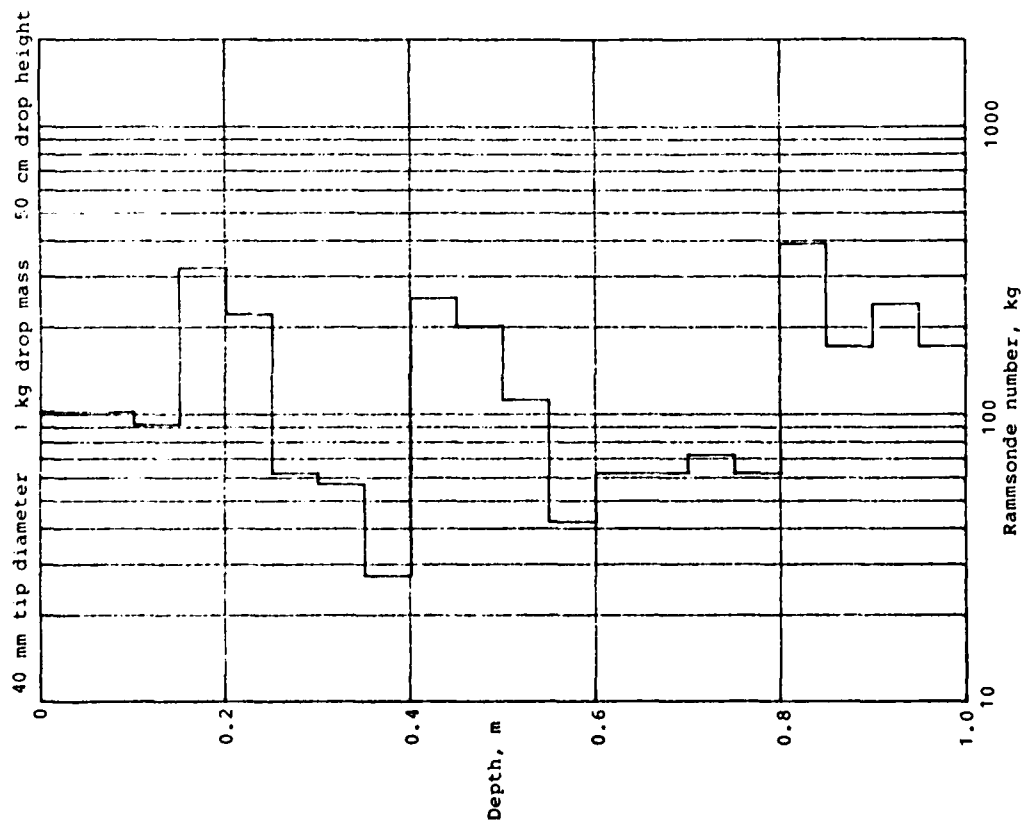
d. Test pavement; 20-mm tip diameter; 3-kg drop mass; 50-cm drop height; 28 January 1984.



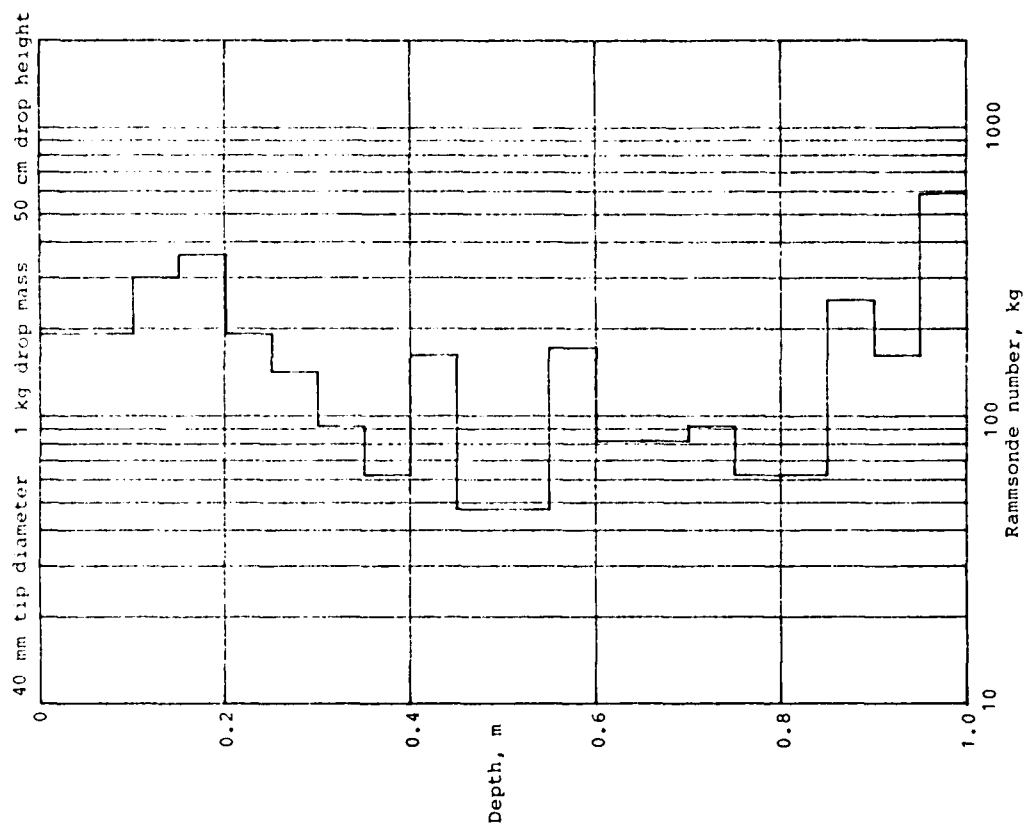
e. Test pavement; 40-mm tip diameter; 9-kg drop mass; 50.8-cm drop height; 28 January 1984.

Figure A21 (cont'd).



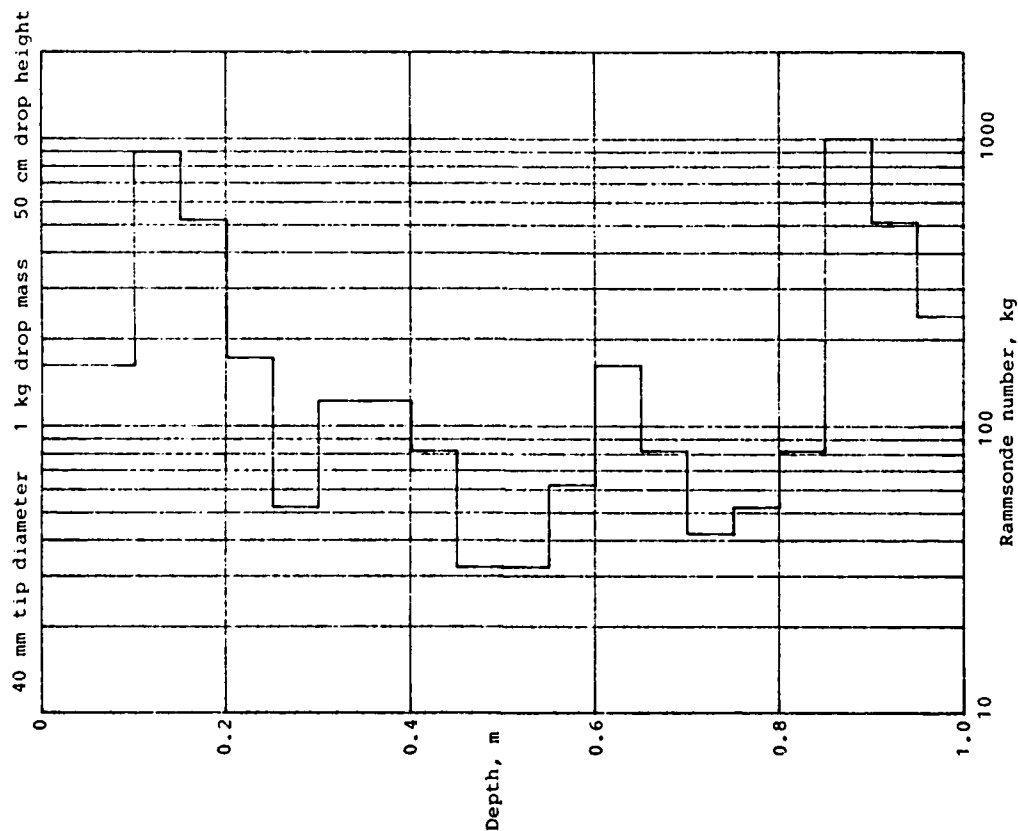


f. Eastern end of runway site; 40-mm tip diameter; 1-kg drop mass; 50-cm drop height; 7 February 1984.



g. Center of runway site; 40-mm tip diameter; 1-kg drop mass; 50-cm drop height; 7 February 1984.

Figure A21 (cont'd). Rammsonde profiles.



h. Western end of runway site; 40-mm tip diameter; 1-kg drop mass; 50-cm drop height; 7 February 1984.

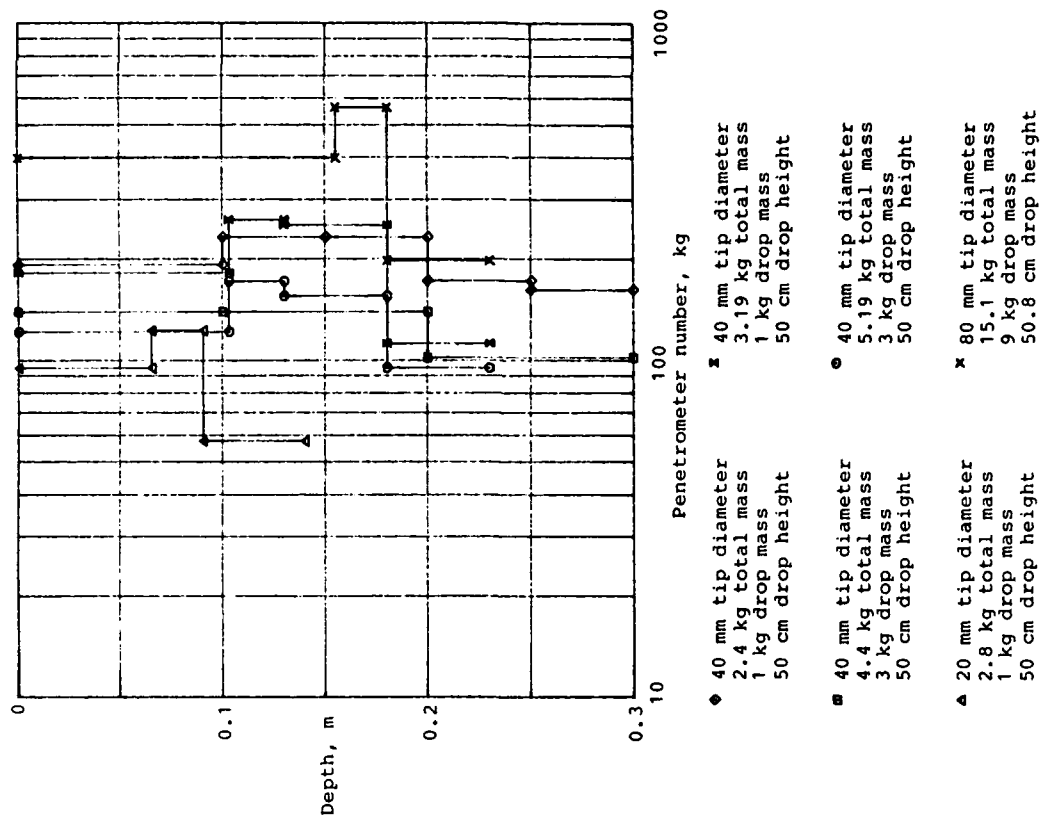


Figure A22. Correlation of different penetrometers in aged drift snow.

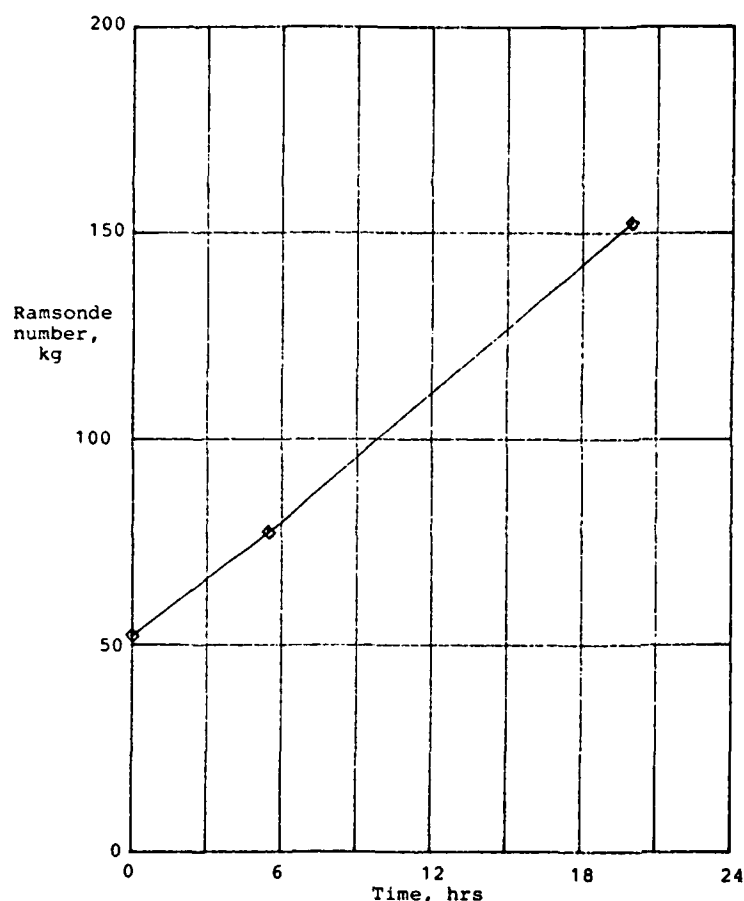


Figure A23. Increase with time in ramsonde hardness of processed snow.

$$R = Wh (n/l) + P \quad (A4)$$

where  $R$  = ramsonde hardness (kg)

$W$  = hammer mass (kg)

$h$  = hammer drop (cm)

$l$  = penetration (cm) for  $n$  blows

$P$  = total penetrometer mass (kg).

The correlation between penetrometers is not good using eq A4 (Fig. A22). It is improved if allowances are made for an energy loss during the impact of the hammer. The loss depends on the relative masses of the hammer and the penetrometer. Another penetrometer number equation is developed later, where the correlation between penetrometers with different hammer masses, penetrometer masses and tip sizes is discussed. Typical ramsonde hardness values, calculated with the improved formula, are also given later.

The increase in ramsonde hardness with aging of processed snow is shown in Figure A23. There

has been a threefold increase within 24 hours of placing the disaggregated snow.

### CBR results

The CBR load-penetration curves for the 17 tests are shown in Figure A24 (Figure A25 shows the locations). The divisions on the load axis are 1 kN for all the graphs. Apart from CBR tests 1 and 2 (which were invalidated due to melting of the test snow by the piston), the maximum piston loads during the 15-minute test period ranged from about 3.2 kN (Test 11 on in situ snow) to about 11.2 kN (Test 15 on icy in situ material).

Table A2 lists the CBR values of each test. The density of the CBR samples, especially of in situ samples, was not uniform. There was a marked difference between the CBR of the icy end of a sample and the snowy end. Table A3 shows the average of the CBRs for both ends of the sample together with the average density of the sample. The values in Table A3 are plotted on a log scale in Figure A26.

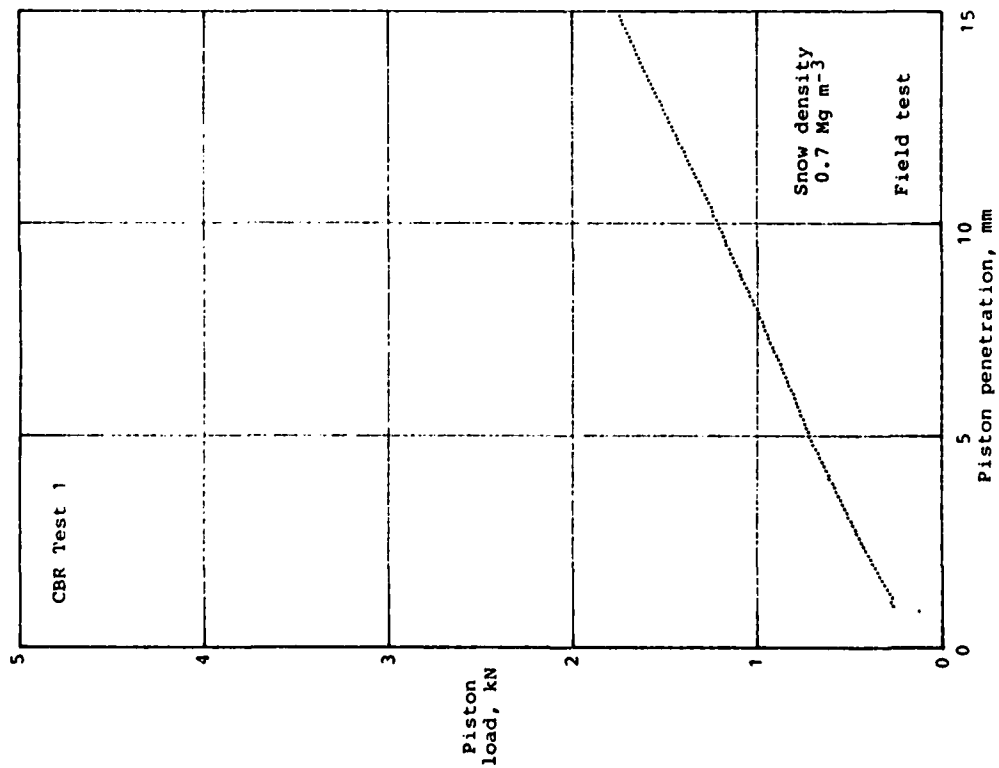
### Plate bearing and creep

The plate test was performed on a section of test pavement 200 mm thick (see Figure A25 for location). Table A4

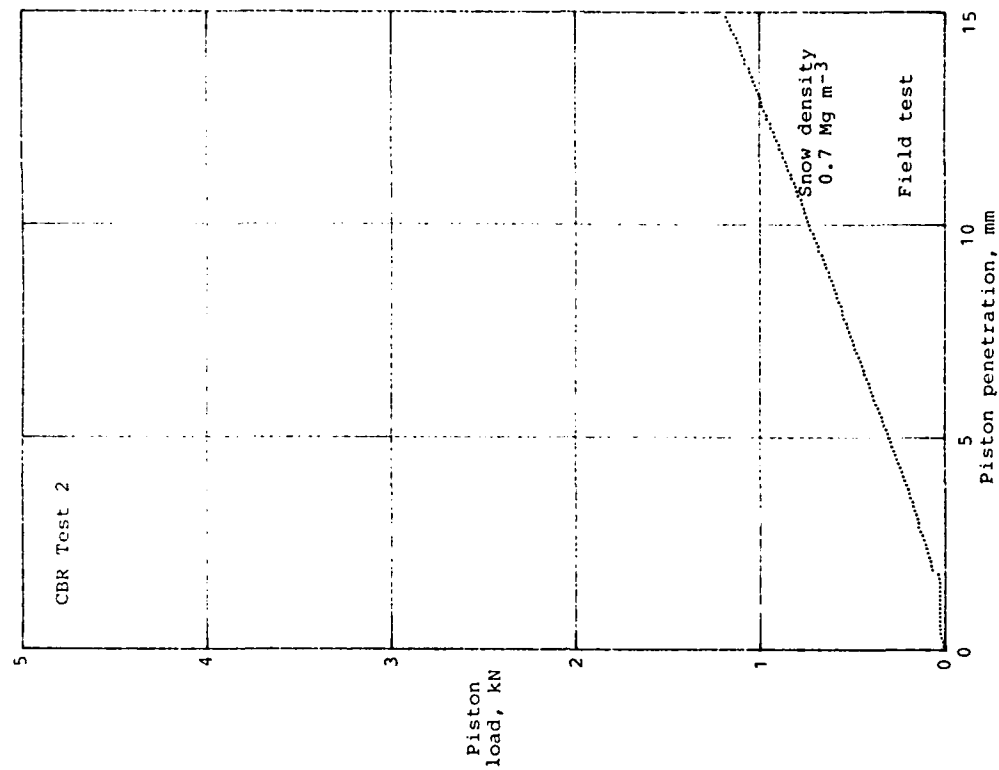
Table A2. CBR values of in situ and pavement snow of different densities.

| Test | CBR (%) | Density ( $Mg\ m^{-3}$ ) |
|------|---------|--------------------------|
| 1    |         | 0.7                      |
| 2    |         | 0.7                      |
| 3    | 16.5    | 0.5                      |
| 4    | 15.3    | 0.5                      |
| 5*   | 29.9    | 0.63                     |
| 6    | 23.9    | 0.56                     |
| 7*   | 49.9    | 0.70                     |
| 8    | 15.9    | 0.50                     |
| 9    | 11.1    | 0.50                     |
| 10   | 29.5    | >0.58                    |
| 11   | 12.6    | <0.58                    |
| 12   | 19.8    | <0.60                    |
| 13   | 60.4    | >0.60                    |
| 14   | 13.4    | <0.62                    |
| 15   | 70.1    | >0.62                    |
| 16   | 23.6    | 0.55                     |
| 17   | 23.5    | 0.55                     |

\* pavement

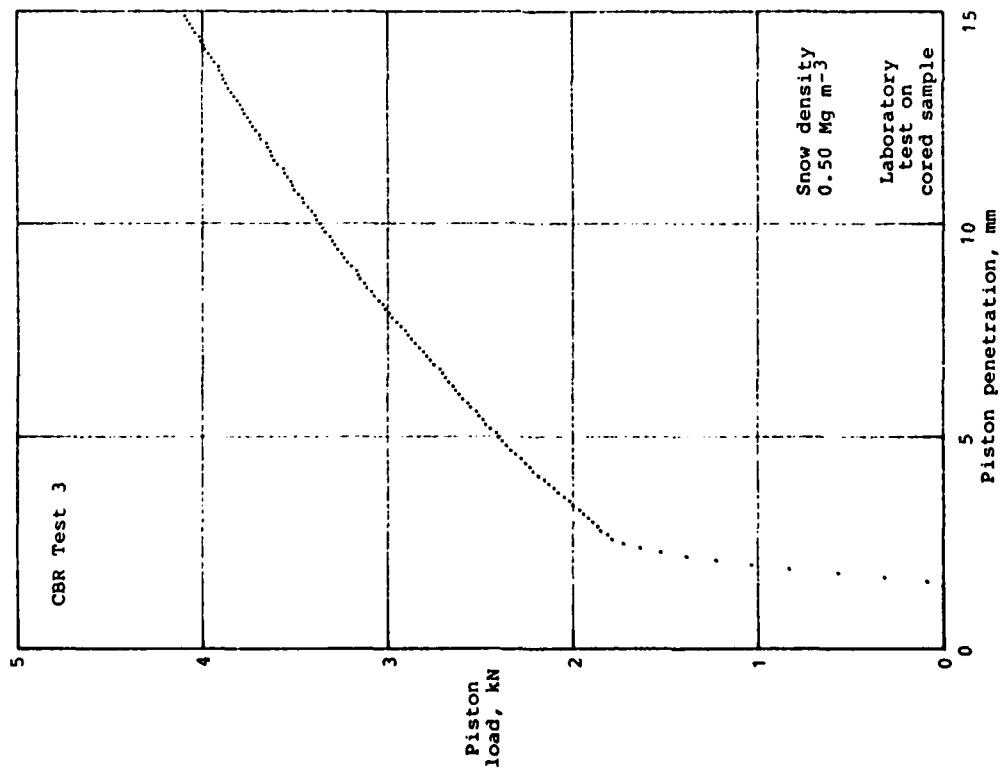


a. Test 1; rolled moist snow. The piston was probably melting into the snow, invalidating the test.

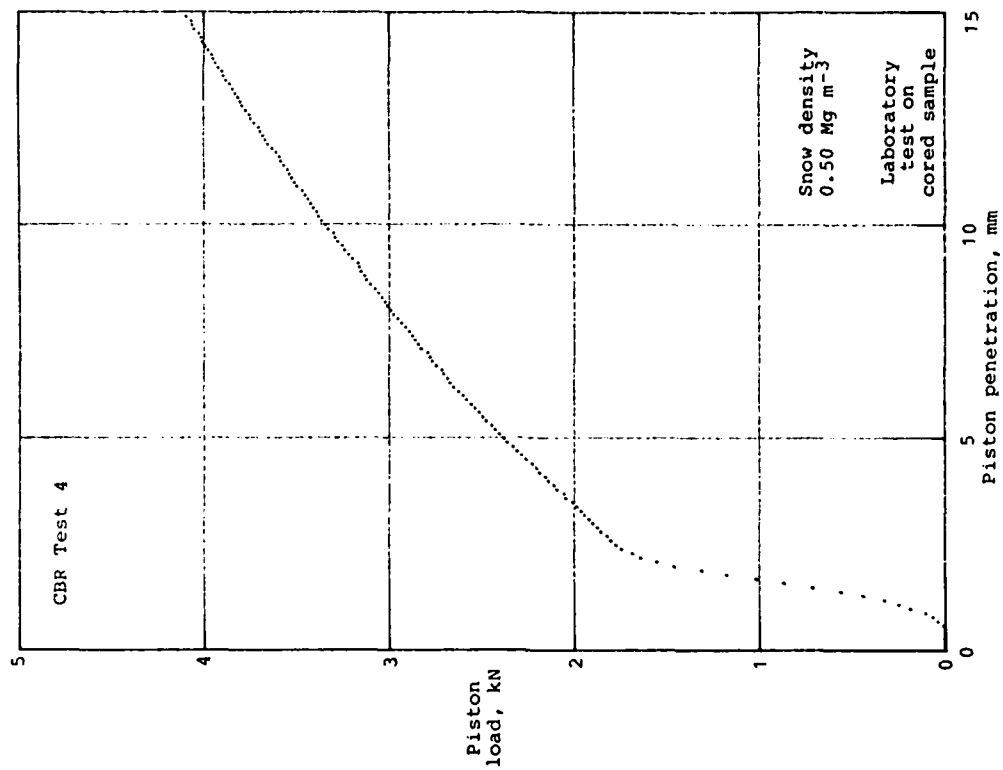


b. Test 2; rolled moist snow. The piston was probably melting into the snow as in Test 1.

Figure A24. CBR test results.

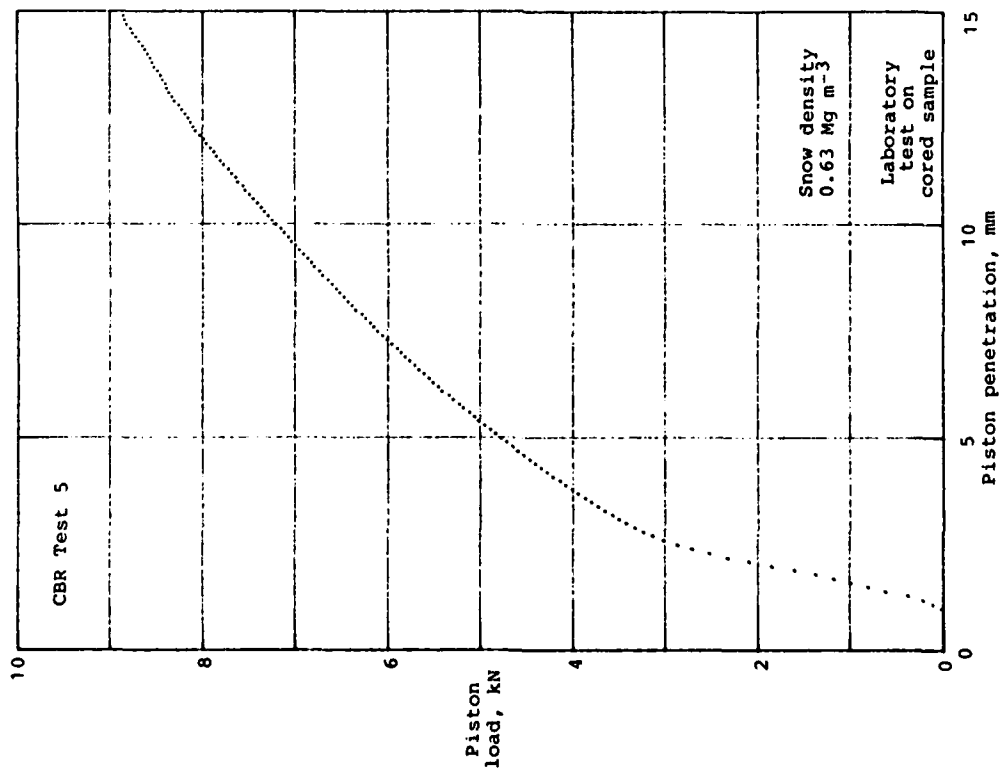


c. Test 3, aged drift snow. This was the first of the laboratory tests on field samples obtained by coring.

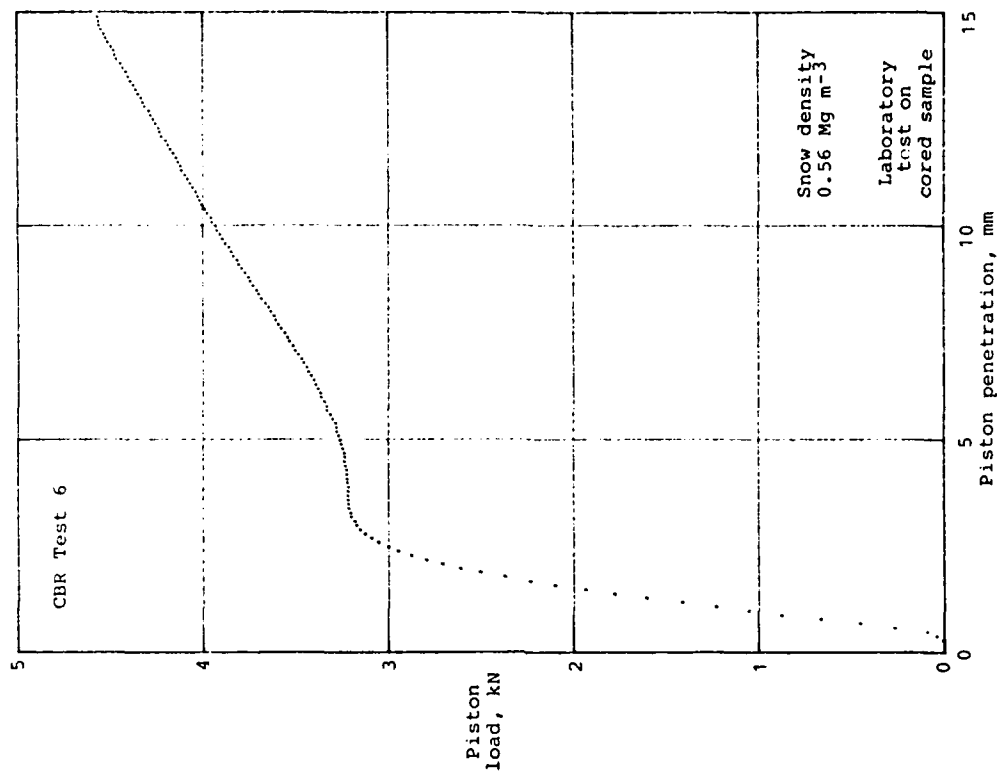


d. Test 4, aged drift snow.

Figure A24 (cont'd). CBR test results.

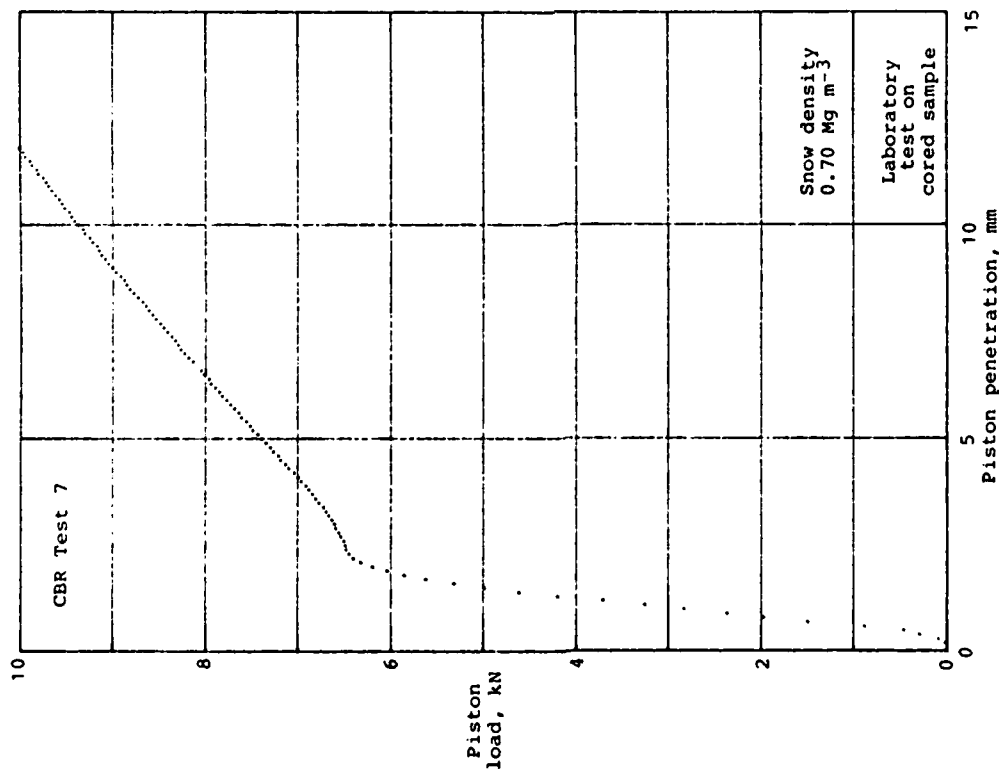


e. Test 5; pavement snow. The sample was tested on the upper face.

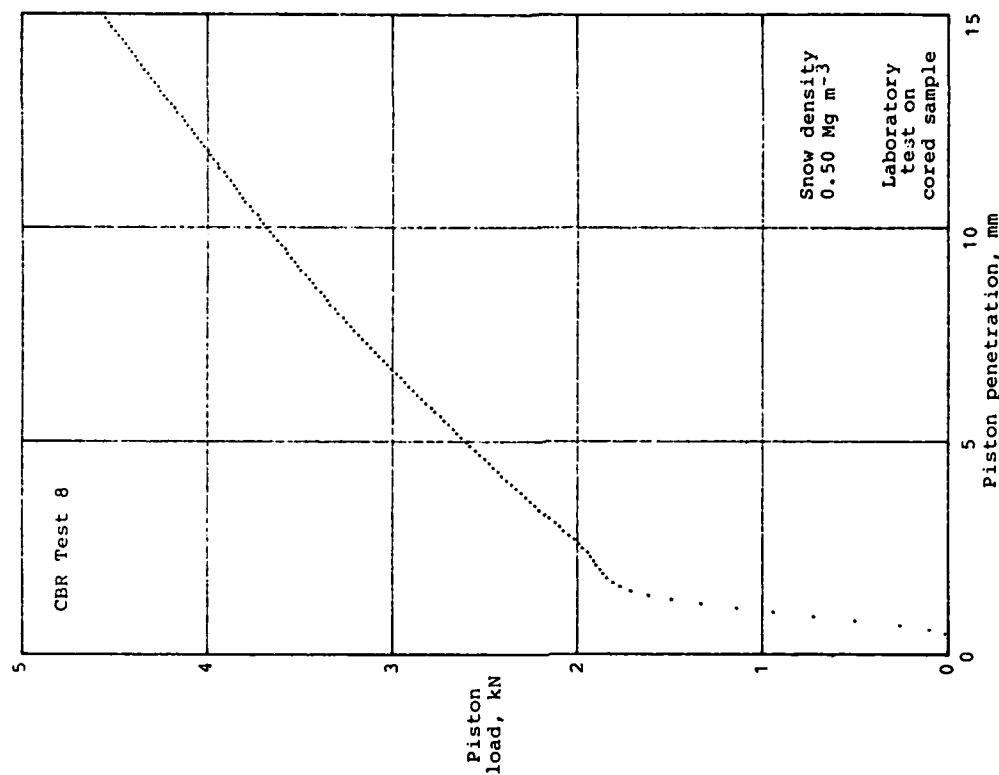


f. Test 6; snow 0.6 m below pavement surface.

Figure A24 (cont'd).

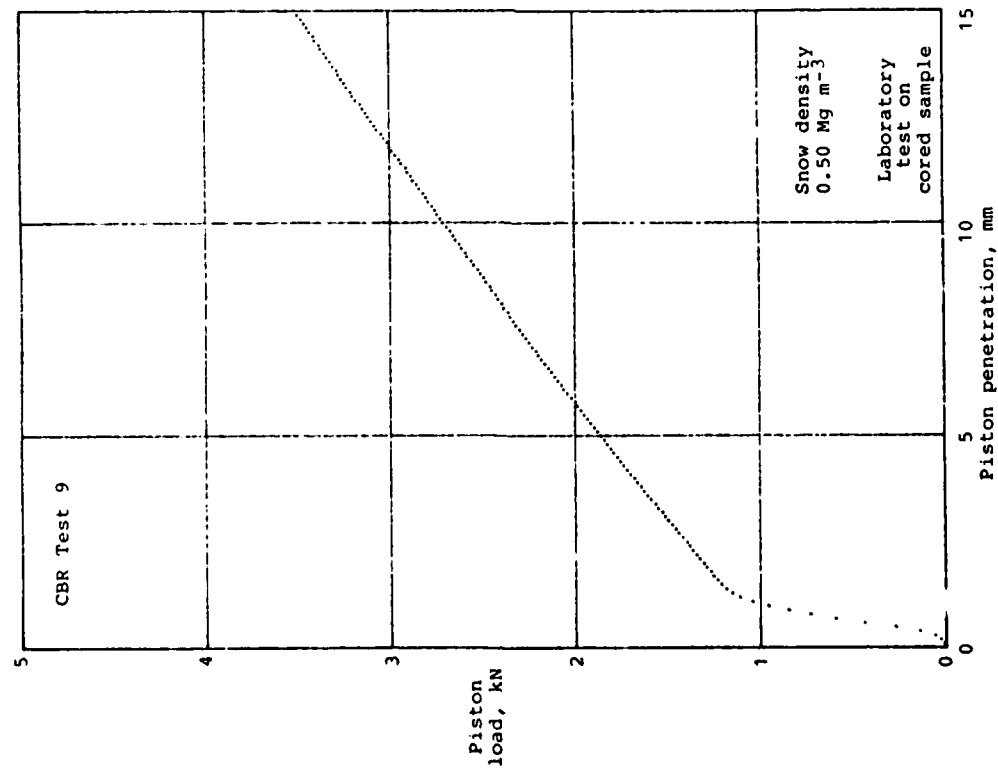


g. Test 7; pavement snow. The sample (also used for Test 5) was tested on the lower face.

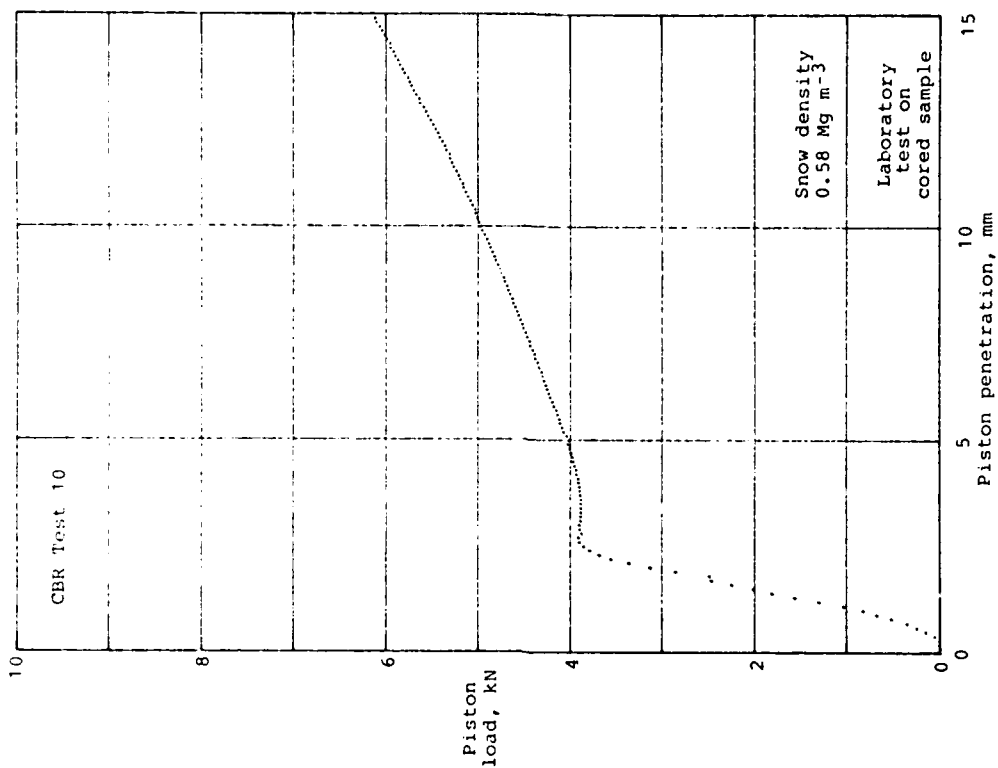


h. Test 8; aged drift snow. The sample was tested on the lower face.

Figure A24 (cont'd). CBR test results.



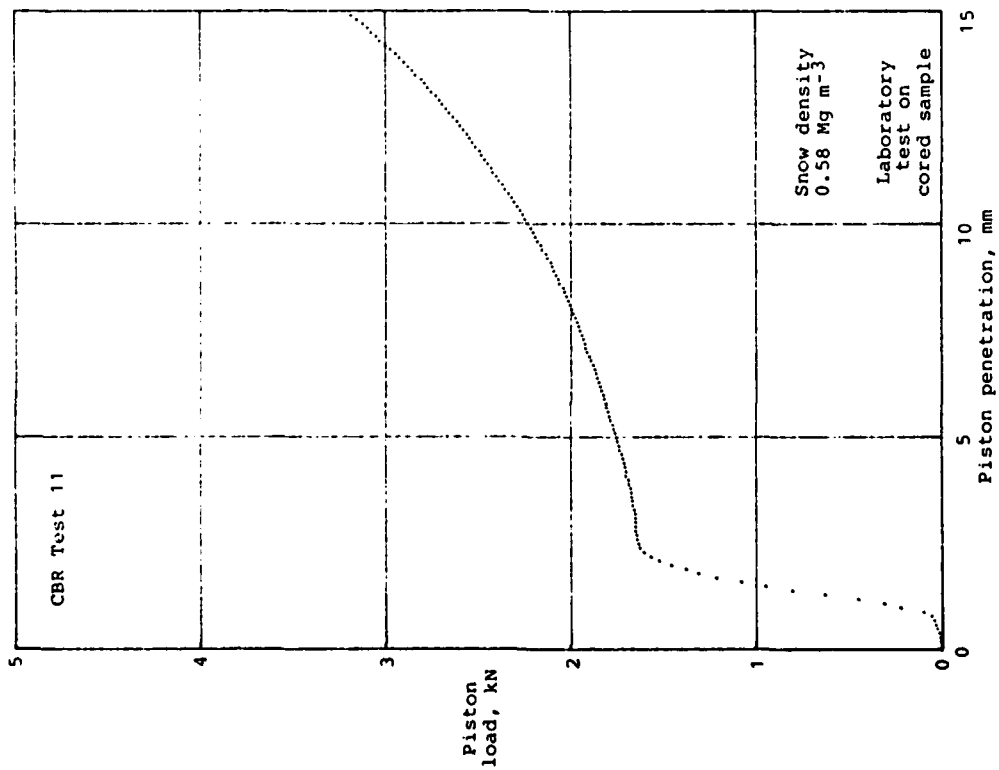
i. Test 9; aged drift snow. The sample (also used for Test 8) was tested on the upper face.



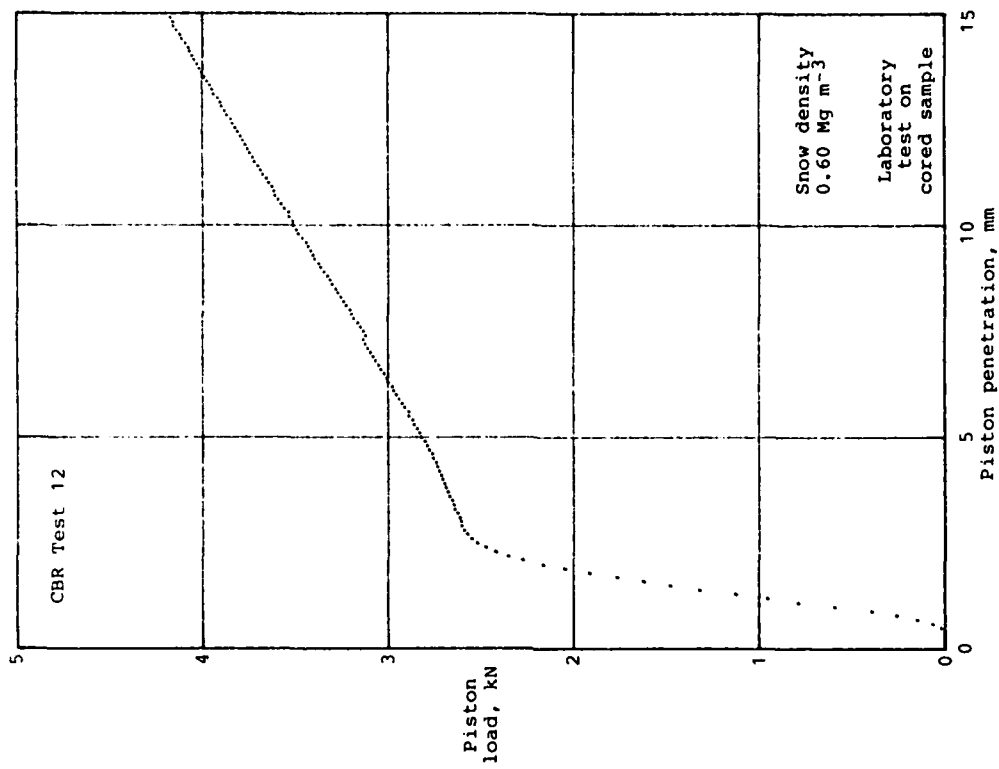
j. Test 10; snow from eastern end of runway site. The sample was tested on the icy side.

Figure A24 (cont'd).



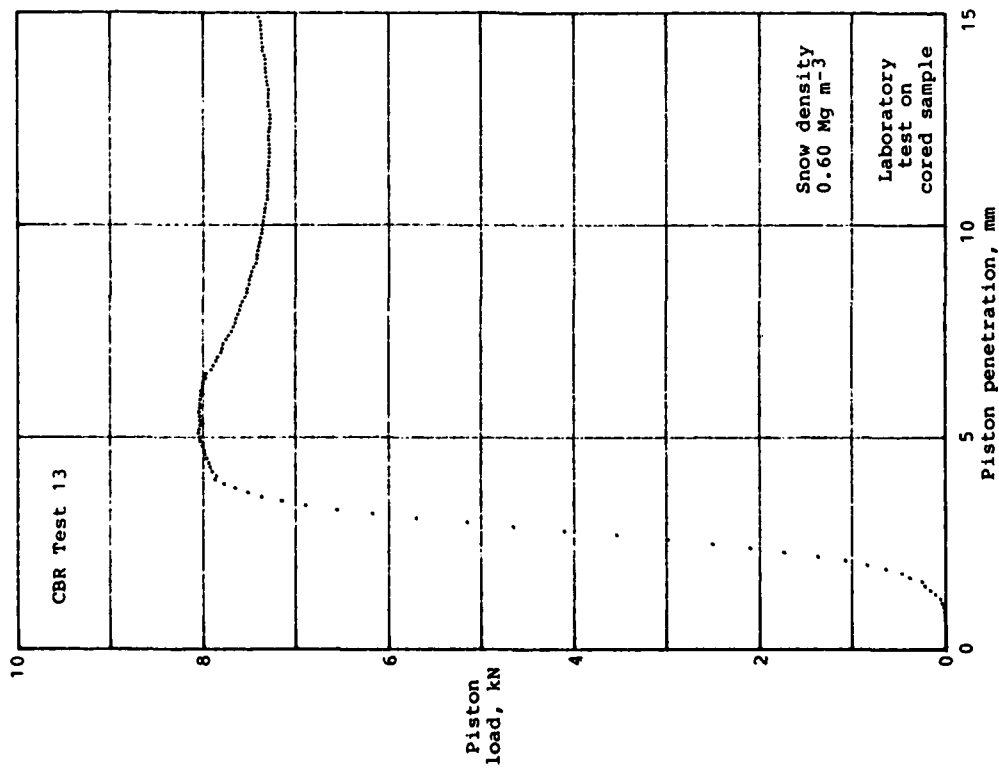


k. Test 11; snow from eastern end of runway site. The sample (also used for Test 10) was tested on the snow side.

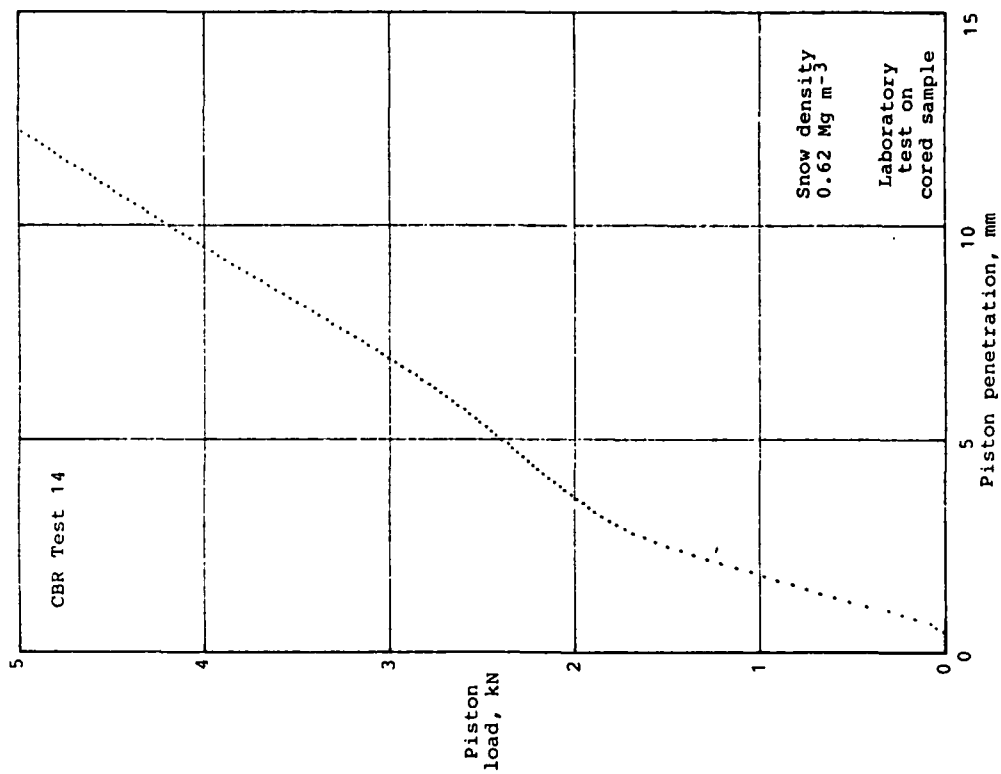


l. Test 12; snow from 0.4 m below the surface at the eastern end of runway site. The sample was tested on the snow side.

Figure A24 (cont'd). CBR test results.

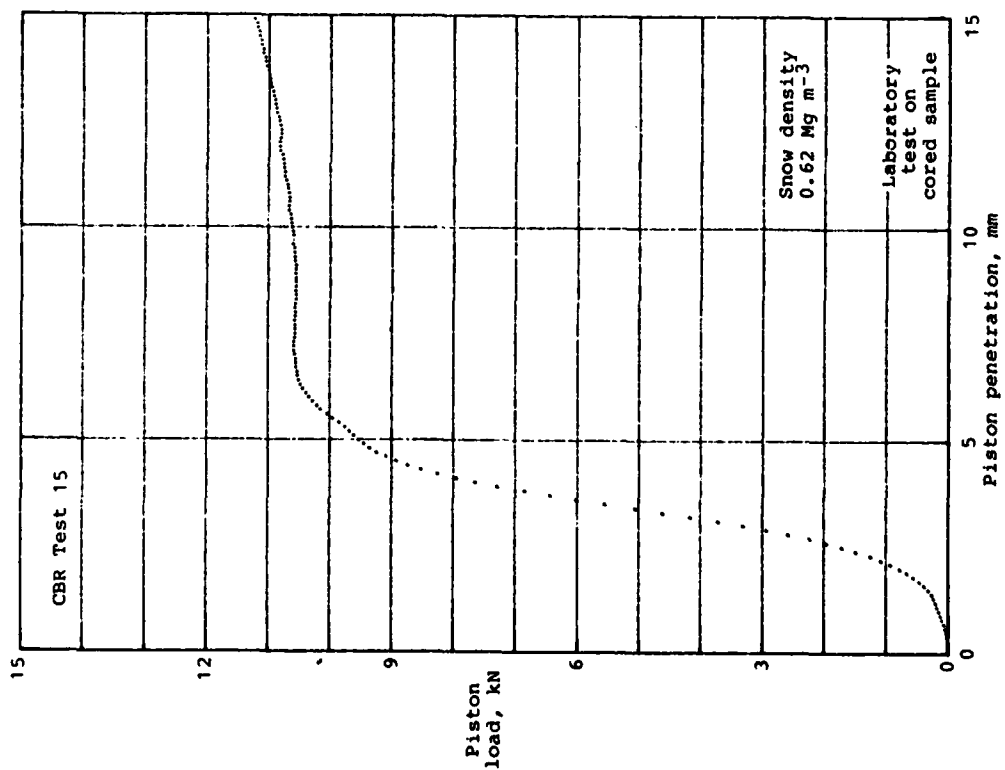


m. Test 13; snow from 0.4 m below the surface at the eastern end of runway site. The sample (also used for Test 12) was tested on the icy side.

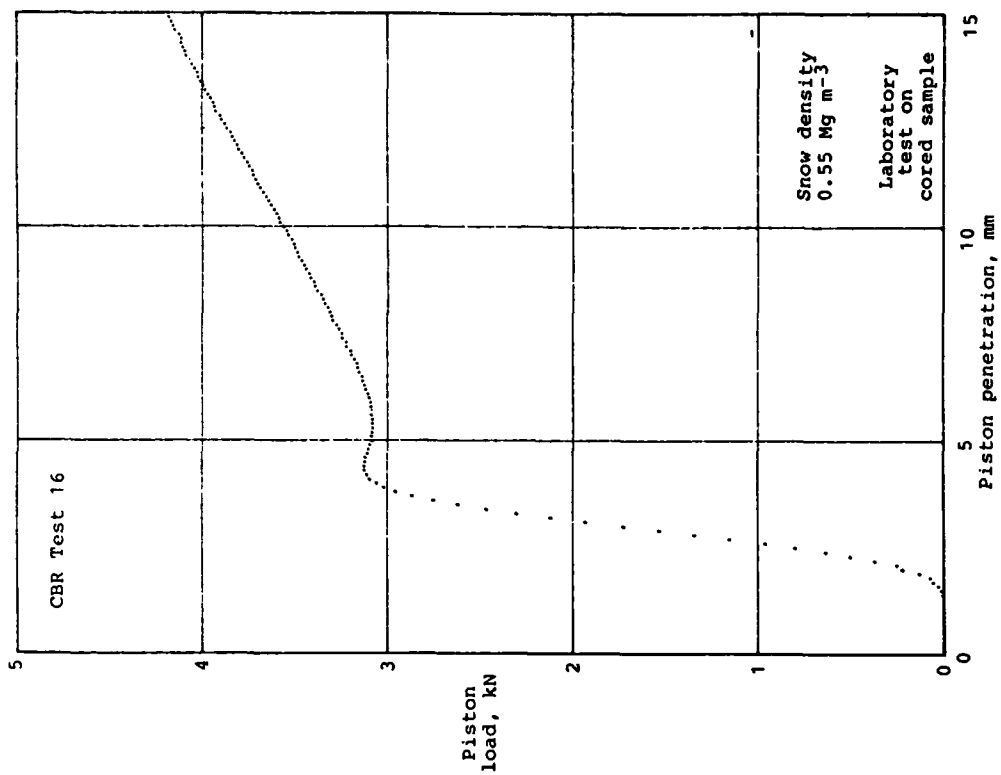


n. Test 14; snow from the surface at the western end of runway site. The sample was tested on the snow side.

Figure A24 (cont'd).

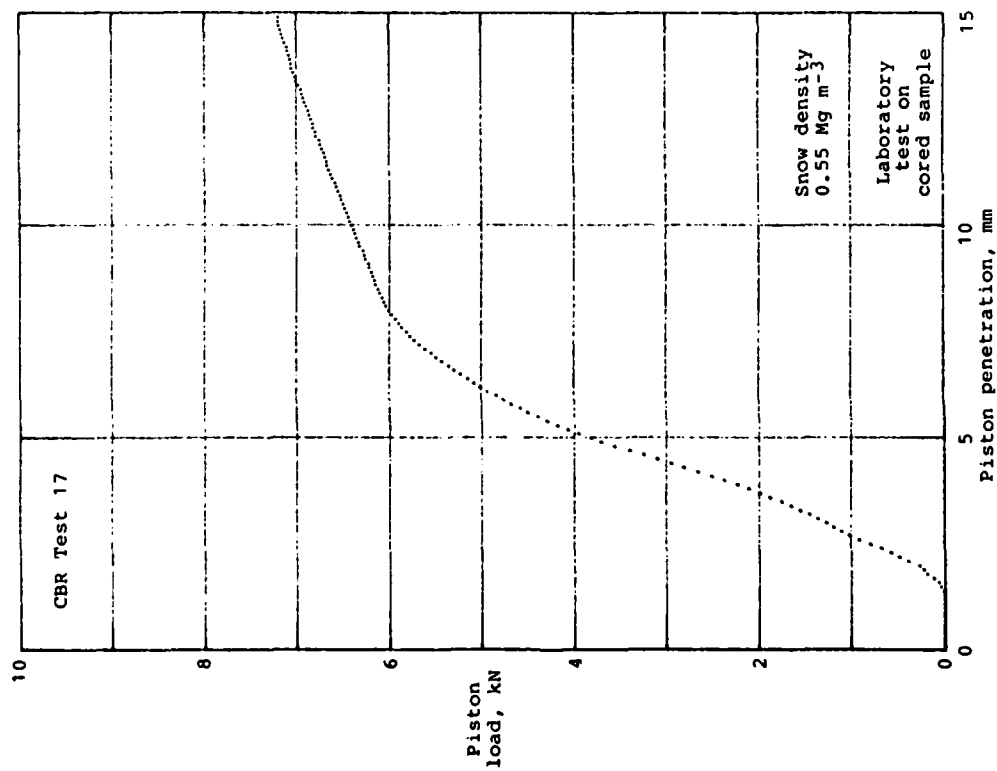


*o. Test 15; snow from the surface at the western end of runway site. The sample (also used for Test 14) was tested on the icy side.*



*p. Test 16; snow from 0.4 m below the surface at the western end of runway site. The sample was tested on the snow side.*

*Figure A24 (cont'd). CBR test results.*



q. Test 17; snow from 0.4 m below the surface at the western end of runway site. The sample (also used for Test 16) was tested on the icy side.

Figure A24 (cont'd). CBR test results.

DO NOT SCALE FROM THIS SKETCH

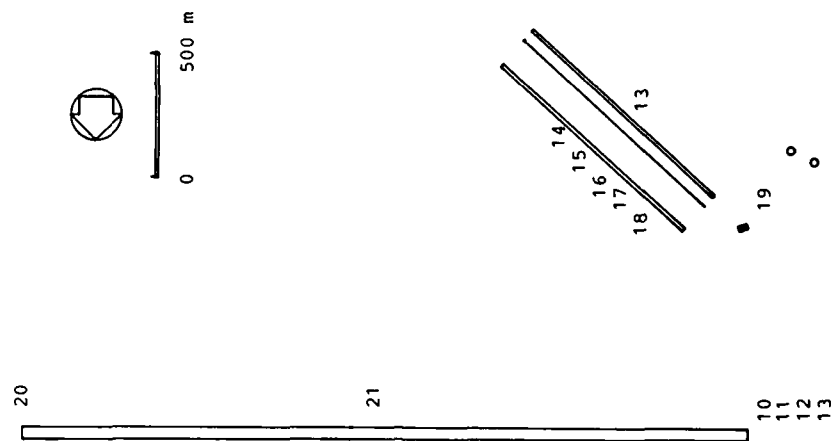


Figure A25. Map of the test area showing the sites of the penetrometer tests.

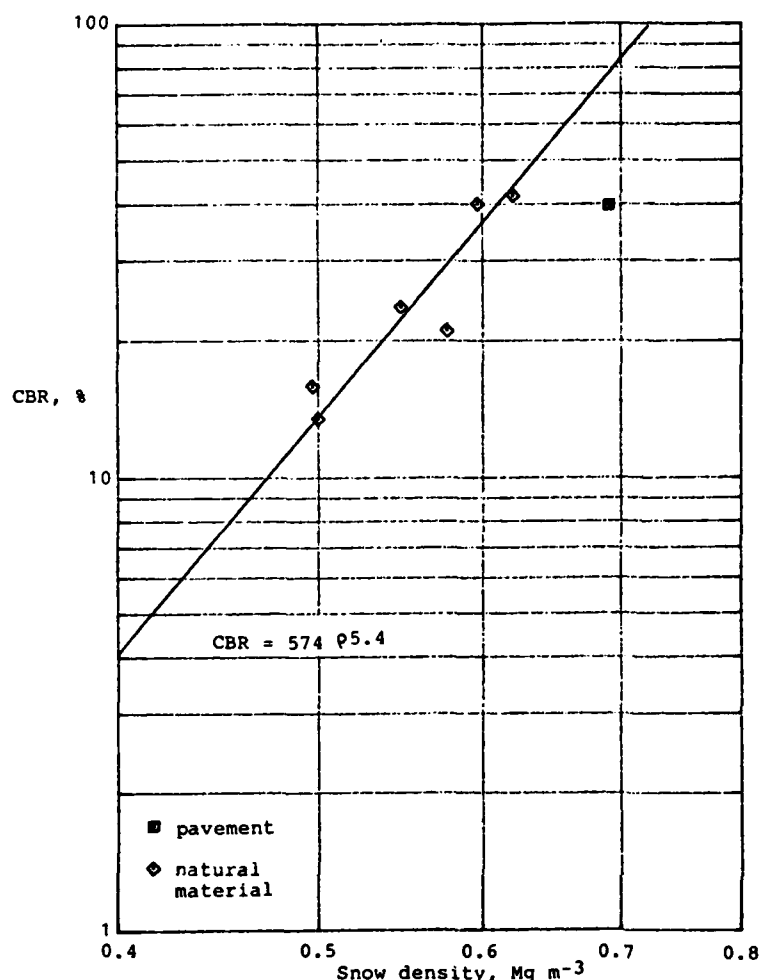


Figure A26. Logarithmic plot of CBR of natural snow vs density. The equation is a least-squares geometric fit. Also shown is the CBR of the test pavement, which had not fully age-hardened.

Table A3. Averaged CBR values for each sample of in situ snow and pavement snow. The density is the average sample density.

| Tests | CBR (%) | Density ( $\text{Mg m}^{-3}$ ) |
|-------|---------|--------------------------------|
| 3,4   | 15.9    | 0.497                          |
| 5,7*  | 39.9    | 0.691                          |
| 8,9   | 13.5    | 0.50                           |
| 10,11 | 21.1    | 0.577                          |
| 12,13 | 40.1    | 0.597                          |
| 14,15 | 41.8    | 0.621                          |
| 16,17 | 23.8    | 0.548                          |

\* pavement

Table A4. Comparison of plate and C-130 tire footprint.

|          | Plate   | C-130               |
|----------|---------|---------------------|
| Load     | 16.2 Mg | 17.6 Mg (one wheel) |
| Pressure | 562 kPa | 586 kPa (85 psi)    |
| Diameter | 600 mm  | 612 mm              |

shows the comparison between the plate and the aircraft tire parameters.

The plate settlement over the three-hour test period is shown in Figure A27. The same data are plotted on log-log scales in Figure A28. Extrapolation to very short and very long times is easier on the log-log plot. The validity of the extrapolations needs to be tested by proof-roller loading.

The total settlement after 2.5 hours was about 13.8 mm. The surface on which the plate was bearing was not flat. The surface undulations were about 10 mm, and therefore the settlement recorded is probably greater than if the surface had been flat. The settlement of the plate after a time equal to the loading time of a C-130 taxiing at 0.5 kph (0.001 h) is on the order of 2 mm. The settlement after standing for 10 hours is about 20 mm. These estimated values are for single passes of a fully laden aircraft.

Although further testing needs to be performed on full-scale pavement (particularly by proof rolling), the pavement as tested here shows adequate strength for a runway pavement. It also appears possible to construct a pavement sufficiently strong to serve as a hard-standing area, without recourse to reinforcement.

#### Meteorological and glaciological records

The data record for air temperature, snow temperature, solar radiation, wind speed and wind direction is tabulated in Russell-Head et al. (1984). The records are in computer files. Graphical records for the period need to be produced from the filed data. Samples of a daily set of graphs are shown in Figure A29.

Once the graphical presentations of the complete data set are available, an assessment of the appropriate type of analysis can then be made (e.g.

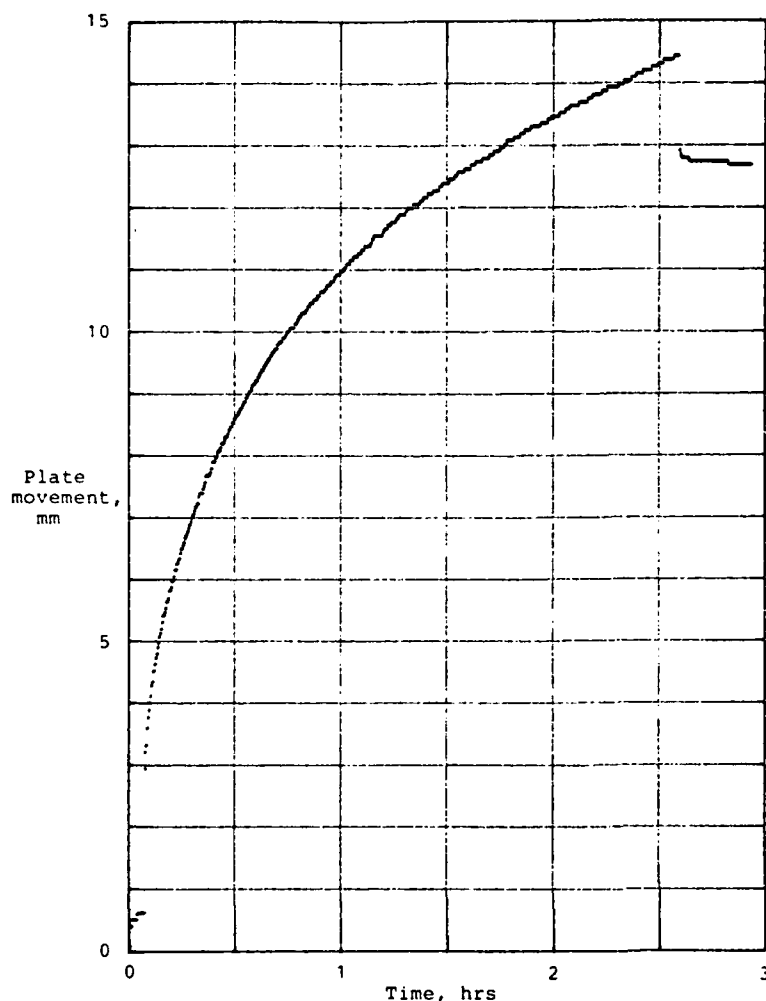


Figure A27. Settlement into the test pavement of a 600-mm-diameter plate loaded to 16.2 Mg. The plate was unloaded after about 2.5 hours.

number of days of significant melt, number of days with wind speed above 15 knots). The analysis will be of use to flight forecasters as well as construction planners.

## ANALYSIS OF DATA

This section brings together the results of the various tests performed on the in situ and processed snow. Relationships between the penetrometer values, CBR and snow density are of prime importance. A set of three equations coupling the three parameters is offered.

The results of the full-scale plate test are matched against values predicted by the settlement analysis of Russell-Head et al. (1982). The requirements of a runway and a hard-standing area are then summarized.

## Comparison of penetrometers

The scatter in Figure A22 shows the problem of determining the average resistance of the snow under test, when penetrometers of differing configuration are used. The variations lie in the differing drop and penetrometer masses (for the 40-mm tip size) and, more obviously, the penetrometer tip size.

## Drop mass and penetrometer mass

The normally used rammsonde equation (eq A4) assumes that all the potential energy of the falling hammer is converted to plastic deformation in the test snow. A number of workers have criticized the limitations of eq A4 and have offered relationships that fit their data better (Niedringhaus 1965, Waterhouse 1966). The authors of this report suggest that the Hiley pile-driving formula as offered by Waterhouse (1966) is the best available, but perhaps it also should be slightly modified.

The Hiley (1925) formula allows for an energy dissipation during the impact of the drop hammer on the penetrometer. The argument follows a set of Newtonian ideas about impacting bodies, where the loss at impact is accounted for by a coefficient of restitution,  $e$ . For perfectly elastic collisions,  $e$  is 1; where there is no rebound after impact,  $e$  is 0.

The Hiley formula as applied to the penetrometer is

$$R = (Wh/s) (W + e^2P) / (W + P) \quad (A5)$$

where  $W$  = hammer mass (kg)  
 $h$  = hammer drop (cm)  
 $s$  = "set" (cm per blow)  
 $e$  = coefficient of restitution  
 $P$  = penetrometer mass (excludes hammer).

In the original rammsonde equation (A4), there is a term covering the effect of the gravity-induced force of the penetrometer acting at the tip, in addition to the impact force. This term is significant for low-density snow and should be included in equation (A5):

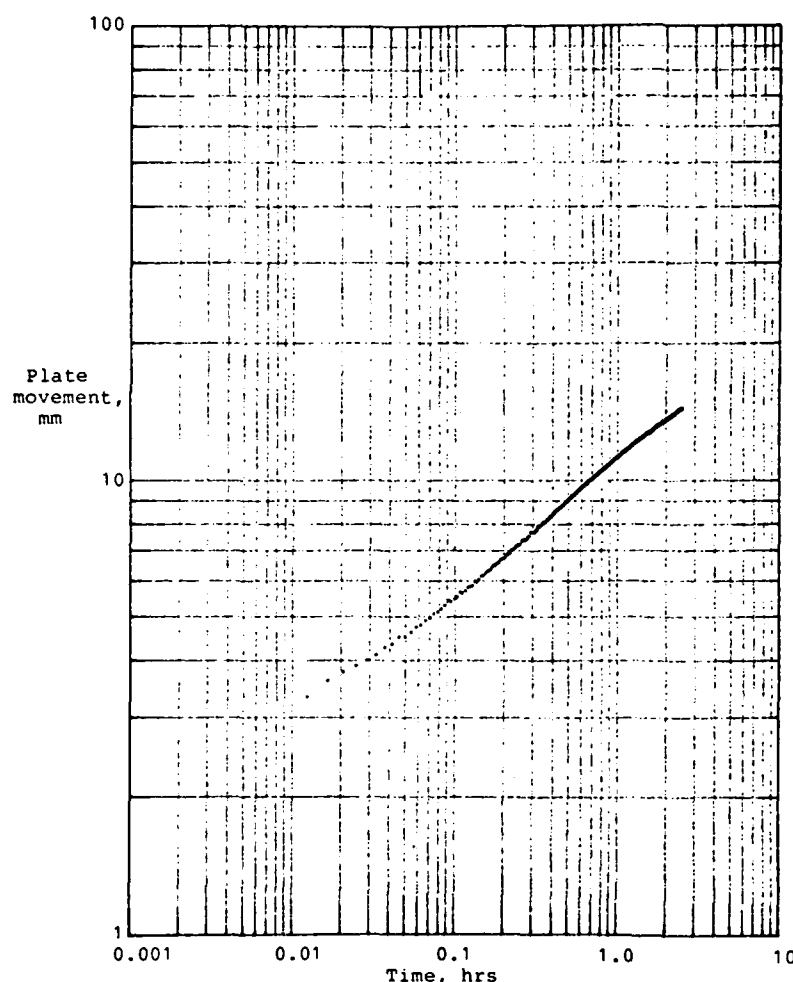


Figure A28. Plate bearing data plotted on logarithmic scales.

$$R = (Wh/s) (W + e^2P) / (W + P) + (W + P) \quad (A6)$$

As the value for  $e$  is about 0.5 for steel/steel (and is reduced if the impacting surfaces are not clean) the rammsonde value as given by eq A6 may be as low as 60% of that by eq A4 when the hammer and penetrometer masses are equal. The spread of  $R$  in Figure A23 for penetrometers of different masses and hammer weights with the standard 40-mm-diameter tip is reduced when  $R$  is calculated with eq A6.

#### Penetrometer tip size

Two tips, 20 mm and 80 mm in diameter, were tested against the standard 40-mm rammsonde tip. The 80-mm tip was tested for its usefulness in low-density snow and was found to have no advantage over the standard rammsonde (Fig. A21a and b). The 20-mm tip was tested in high-density (pavement) snow, and it offers easier penetration while

giving the same information as the rammsonde (Fig. A21d and e).

The penetrometer number, as given by penetrometers with tips of the same geometry but different diameters, appears to be a function of the cross-sectional area of the tip. Equation A6 can be modified again by scaling according to the ratio of the tip area to the standard rammsonde tip area:

$$R = (d/40)^2 [(Wh/s) (W + e^2P) / (W + P) + (W + P)] \quad (A7)$$

where  $d$  is the diameter of the non-standard tip (mm).

The return angle from the maximum diameter of the tip to the shaft may also be important, and unfortunately the angle of the three tips tested on site were different. The half-angle of the standard rammsonde is about  $9.4^\circ$ ; for the small tip it was  $2.5^\circ$  and for the large tip it was  $20^\circ$ .

The higher-than-expected (by eq A7) values of the small tip may be due to the small rear clearance, and likewise the lower-than-expected values of the large tip may be due to the generous rear clearance. More work should be done to clarify the tip size effect by using tips with the standard rammsonde clearance angle.

#### Relationship between penetrometer number and snow density

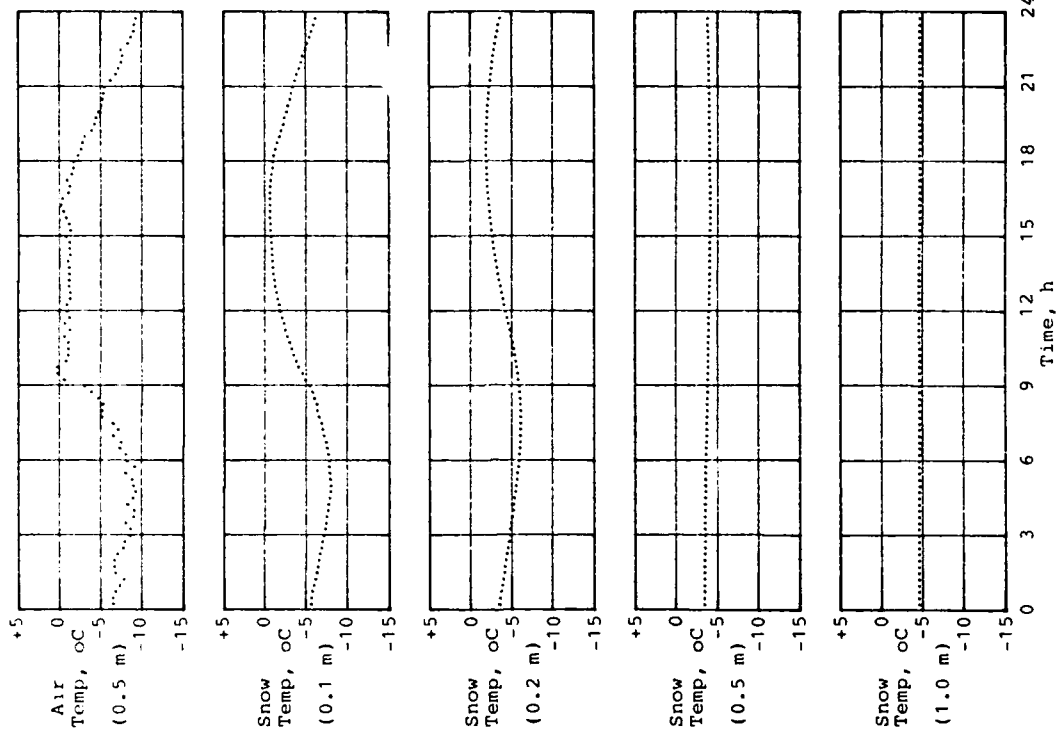
Table A5 lists standard rammsonde values with snow densities selected from Figure A21. There are not many situations where the snow density is sufficiently uniform for a rammsonde number to be ascribed to a density.

The lowest  $R$  value is for the in situ case where the rammsonde is within ice lenses. There are two intermediate density situations that can be used for the correlation. One is the  $R$  of the aged drift snow, which had a fairly uniform density. The other is to average a complete pro-

Table A5. Values of standard rammsonde hardness for snow of uniform density.

| $R$ (kg) | $r$ (Mg <sup>-1</sup> ) |
|----------|-------------------------|
| 5025     | 0.7                     |
| 88       | 0.5                     |
| 77.5     | 0.48                    |
| 19.3     | 0.42                    |

5Feb84  
Day 36



5Feb84  
Day 36

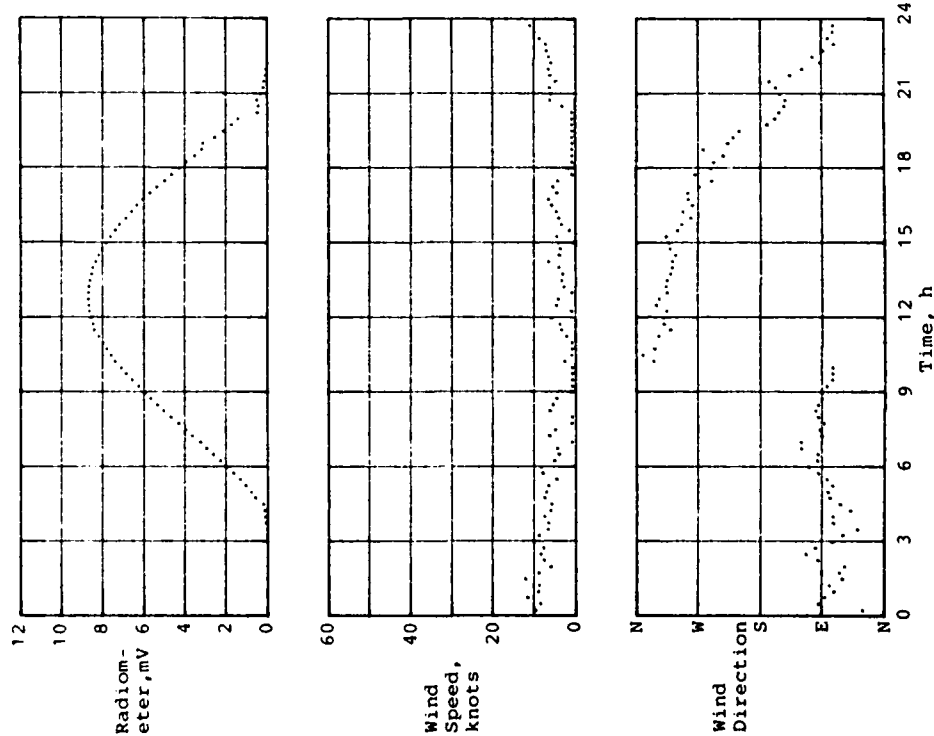


Figure A29. Weather measurements at Lanyon Junction on 5 February 1984.



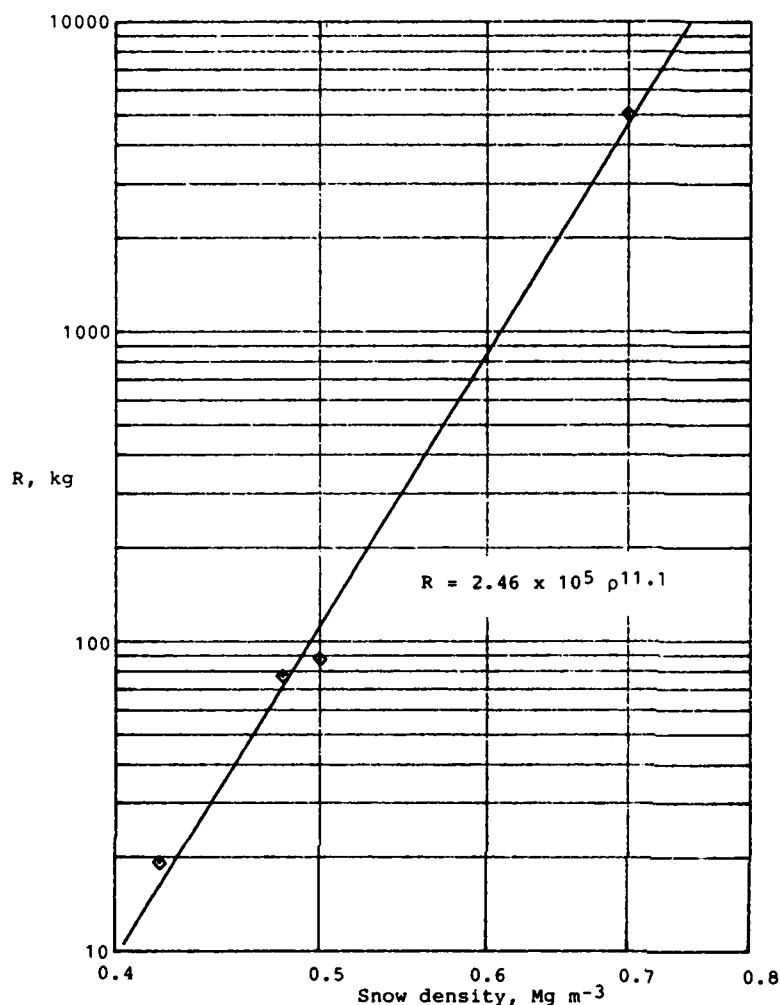


Figure A30. Relationship between rammsonde hardness and snow density for aged snow.

file through in situ snow where the average density is known. The profile at the western end of the strip site was averaged and matched with the average density from the cores near the station.

The high-density case was provided by the pavement. The average maximum value, which coincided with the top of the base course, was used. This snow was aged longest and therefore fits best with the fully aged in situ snow. The penetrometer tip had also been sufficiently deep to avoid surface effects, which significantly reduce the hardness values (Neidringhaus 1965).

The values in Table A5 are plotted against log-log scales in Figure A30. The straight line is a geometric regression fit and has the equation

$$R = 2.46 \times 10^5 r^{11.1} \quad (\text{A8})$$

where  $r$  is the snow density ( $\text{Mg m}^{-3}$ ).  
The inverse of eq A8 is

$$r = 0.327 R^{0.090} \quad (\text{A9})$$

#### CBR of in situ material

The CBR values in Table A3 are plotted on a log scale against density in Figure A26. The points for the in situ material fall about a straight line, implying a power-law relationship. A geometric regression gives the equation

$$\text{CBR} = 574 r^{5.4} \quad (\text{A10})$$

where CBR is in %.

Equation A10 has the inverse:

$$r = 0.308 \text{CBR}^{0.185} \quad (\text{A11})$$

The ice lensing within the in situ material gives rise to large CBR values, but the ice content averages about 16% of the in situ material. The average density is about  $0.48 \text{ Mg m}^{-3}$ , and this corresponds to an average CBR of 10.9%.

The lowest density of the in situ snow is about  $0.42 \text{ Mg m}^{-3}$ , and according to eq A10 has a CBR of about 5.3%. The layered structure is sufficiently consistent to allow the use of the higher (average) CBR of 10.9% in estimating the pavement performance, provided that the covering pavement sufficiently protects the structure.

#### CBR of processed snow

Only one sample of pavement snow was able to be tested. The density of the sample was not uniform, and there was a significant difference in the CBR values obtained from each end. The CBR of the denser end was 49.9%, and for the less dense end (corresponding to the pavement surface) it was 29.9%. The average of the CBRs from both ends was 39.9%.

Plotted on Figure A26, the point for the average CBR and average density ( $0.691 \text{ Mg m}^{-3}$ ) is below the line applicable to the in situ CBRs. This is most likely due to the short period of age-hardening of the pavement snow. The CBR for  $0.691 \text{ Mg m}^{-3}$  by eq A10 is 78%, which is twice the measured value.

It seems reasonable to expect that the pavement CBR would substantially increase with further aging.

#### Correlation of penetrometer hardness and CBR

Equation A8 relates the standard rammsonde hardness to snow density, and eq A10 relates the CBR to snow density. These two equations can be used to derive a third equation, the CBR to rammsonde hardness relationship:

$$CBR = 1.68 R^{0.432} \quad (A12)$$

and the inverse:

$$R = 0.303 CBR^{2.3} \quad (A13)$$

The  $R$  value is the standard rammsonde hardness as calculated by eq A6. The CBR value is from a test with a piston speed of 1 mm per minute. The standard American test speed is 0.050 inches per minute (1.27 mm per minute). It is likely that the 27% higher piston speed will give different CBR values. Some allowance may need to be made when comparing CBR values if test speeds are not the same.

#### Temperature and age effects on snow strength

The testing program did not address these problems directly, and little quantitative data were collected at the site. The temperature effect on CBR and rammsonde hardness cannot be ascertained at this stage, although it is clear that there is a substantial loss of strength at snow temperatures above  $-1.5^{\circ}\text{C}$ .

An aging effect on strength was qualitatively observed at the site. It seemed to be temperature related in that age-hardening occurred more quickly at high temperatures. The only quantitative information, the increase in rammsonde hardness of processed snow, is shown in Figure A23. The three-fold increase in  $R$  indicates a probable doubling of the CBR value. The aging of processed snow is also likely to depend on the particle size distribution, as well as snow density and temperature.

The data set required to adequately quantify the temperature and aging effects would be quite large. The expense is probably not justified for the Casey runway, where adequately high CBR values can be easily reached. However, the performance of the runway at high ambient temperatures and high incident radiation should be investigated. It is

important that the runway pavement is sufficiently thick to accept some surface weakening and remain operationally safe.

#### Pavement performance

The plate test results and CBR determinations provide the opportunity to compare actual pavement performance with calculated predictions. The next section outlines the calculations using the method of Russell-Head et al. (1982).

#### Calculation of settlement

Table A6 lists the pertinent properties of the test pavement and plate. The calculation that follows uses the Burmister (1945) two-layer system theory as given by Poulos and Davis (1974).

The values of elastic modulus  $E$  were obtained from Russell-Head et al. (1982), and the value of the displacement factor  $I_p$  is from Poulos and Davis (1974).

$$\begin{aligned} \text{Settlement} &= 1.5 (p_a / E_2) I_p \\ &= 3.2 \text{ mm.} \end{aligned} \quad (A14)$$

#### Observed plate settlement

The plate movement with time is shown in Figures A27 and A28. As mentioned earlier, the surface of the pavement was not flat, and there is more settlement than if it had been flat. The elastic modulus values in Russell-Head et al. (1982) are derived from CBR tests and therefore have a time factor inherent to the CBR test. Therefore the settlement calculation is applicable for a few minutes of loading.

The plate settlement after a few minutes was 4–5 mm, and as discussed earlier, is probably higher than that for a flat surface. Taking this factor into account, the match with the calculated value is reasonable.

**Table A6. Plate and pavement parameters for the plate load test.**

|                            |                                |
|----------------------------|--------------------------------|
| CBR of pavement            | 40%                            |
| $E$ of pavement ( $E_1$ )  | 383 MPa                        |
| CBR of subgrade            | 10%                            |
| $E$ of subgrade ( $E_2$ )  | 38 MPa                         |
| $E_1/E_2$                  | 10.1                           |
| Pavement thickness, $h$    | 350 mm (including base course) |
| Plate radius, $a$          | 300 mm                         |
| Dead weight                | 16.2 Mg                        |
| Plate load                 | 159 kN                         |
| Plate pressure, $p$        | 62 kPa                         |
| Displacement factor, $I_p$ | 0.48                           |

The settlement calculated is for a few minutes loading and will probably overestimate the tire rut for a moving aircraft. On the other hand the settlement after prolonged loading will be a number of times the calculated value.

Although there may be room for more refinement in the pavement analysis, the general outcome of the plate test is clear. The test pavement is adequately strong for C-130 operation. The degree of adequacy suggests that hard-standing areas for fully laden aircraft could be made from compressed snow as well.

#### Design parameters for snow pavement at Lanyon Junction

The test pavement was shown to be adequately strong for operation by wheeled C-130 aircraft. The pavement course itself is fairly thin at 200 mm, and the base course makes an important contribution to the overall strength of the pavement.

The question of allowing a thinner pavement to be used in the design of the Lanyon Junction site arises. The most difficult problem is the lack of knowledge about the softening and melting during the warmest days. The denser the pavement, the less this problem will be, but it may be easier at first to build a thicker pavement than a denser one.

The test pavement appears to be a reasonable model for the design of the runway at Lanyon Junction. Table A7 summarizes the parameters for runway construction, according to present knowledge. These requirements may be modified in the light of further field tests.

**Table A7. Parameters for pavement construction at Lanyon Junction (with an average sub-grade density of  $0.48 \text{ Mg m}^{-3}$ ).**

|                               |                          |
|-------------------------------|--------------------------|
| Minimum pavement thickness    | 200 mm                   |
| Minimum base-course thickness | 100 mm                   |
| Minimum pavement density      | $0.65 \text{ Mg m}^{-3}$ |
| Minimum base-course density   | $0.58 \text{ Mg m}^{-3}$ |

The requirements of a hard-standing area may be met by the pavement as specified in Table A7. Settlements of a few centimeters while a fully laden aircraft is stationary would seem acceptable. If a smaller settlement is demanded, the snow density could be increased by additional rolling at high roller mass and high tire pressures during the warmer days of the summer period. There does not appear at this stage to be a need for additional reinforcement (e.g. aluminum matting) of a com-

pressed snow pavement at the Lanyon Junction site.

#### In situ testing of pavement

The density of the snow is the most important parameter for assessing pavement performance. While it may not be easy to obtain cores from the pavement, the direct measurement of the density from core samples is probably the most reliable way of checking the quality of the pavement.

The next best check is to perform rammsonde profiling. A new penetrometer should be constructed with a 20- to 25-mm-diameter tip with the same geometry as the rammsonde. Routine profiling through the pavement zone and into the sub-grade is a quick method of checking uniformity of the pavement thickness during the production phase. The standard rammsonde values can be used to assess the present strength and also to monitor age-hardening. The density value should be used to estimate the aged strength.

The CBR tests are neither quick nor easy, but they do give the strength of the snow directly. The field method should not be used, and samples should be obtained from site and tested in a machine in a cold laboratory.

#### CONCLUSIONS AND RECOMMENDATIONS

The density of the in situ snow is greater than had been previously estimated. Earlier work suggested that the pavement thickness would be in the 0.3- to 0.8-m range. The total pavement thickness (pavement plus base course) of compacted snow with an average density of  $0.63 \text{ Mg m}^{-3}$  is now estimated to be about 300 mm.

Relationships between rammsonde hardness, CBR and density have been found for in situ snow, and these compare well with data from other sites and laboratory studies.

The construction equipment was able to produce a base course and pavement with sufficiently high density. A section of pavement was tested to C-130 loads with a 600-mm-diameter plate loaded by 16.2 Mg, giving a pressure of 562 kPa. The average settlement after 2.5 hours was less than 10 mm. The calculated settlement for a fully laden aircraft stationary for a few minutes is less than 5 mm, which is in good agreement with the observed plate behavior.

The equipment for snow testing was generally quite suitable for assessing the strength character-

istics of the in situ and processed snow. The outcome of the testing program is that the pavement as produced in the trial construction is adequately strong for wheeled C-130 operation.

The results presented here are recommended as the basis for a design specification of the pavement for the Lanyon Junction runway for operation by wheeled aircraft. The density profile should be used as the primary parameter for compressed snow runway design and construction control.

Laboratory CBR tests should be performed regularly during the construction period to directly assess the snow strength. A cold laboratory should be maintained on site for this and other snow testing purposes.

The rammsonde penetrometer should be used as the primary depth profiling instrument. A small-diameter rammsonde with the standard tip geometry should be developed for profiling dense snow. The instrument should be used regularly during construction to check pavement thickness and age-hardening.

Snow tests should be performed in accordance with a set of standard procedures to ensure compatibility with the design specifications. Proof rolling to simulate full C-130 loading should also be used at the final stages of the initial construction to verify the performance of the entire length of runway.

Further laboratory work should be done on pavement weakening by summer melting. A section of test pavement should be made early in the construction period and monitored for strength throughout the summer melt period.

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## APPENDIX B: A DESIGN AND TESTING MANUAL FOR THE CONSTRUCTION OF COMPRESSED-SNOW RUNWAY PAVEMENTS\*

### SUMMARY

This appendix describes methods of designing and testing compressed-snow pavements for aircraft use. The methods are based on the results of laboratory and field investigations. The design of a compacted-snow pavement is governed by the aircraft type and the strength of the site material. The data collected during the 1983-84 summer site investigation and construction trials at Lanyon Junction on the Law Dome, near Casey, Antarctica, are used in an example design of a pavement for use by C-130 aircraft at that site. Generalization to other sites and aircraft is indicated.

Wheel settlements are calculated using Burmister's elastic theory of two-layer systems. The elastic moduli needed for the analysis are obtained from the results of California Bearing Ratio (CBR) tests. The modulus value of snow depends mostly on its density but is also influenced by its temperature and age. Settlement charts are presented for a range of pavement thicknesses and densities and strength of the lower layer (subgrade). Techniques are outlined to measure the strength of the subgrade.

The methods for testing the pavement during and after construction are described. The primary pavement parameters are density, thickness and temperature. Procedures for monitoring the strength of the pavement by rammsonde profiling and CBR tests are given. Plate bearing testing and proof rolling are the best methods of simulating aircraft wheel loading. A testing schedule for the runway and taxiway pavement and hard-standing apron pavement is outlined.

### INTRODUCTION

This appendix addresses the problem of the design and testing of compacted-snow runways for wheeled aircraft for sites on the Antarctic ice sheet or similar locations. A separate report has been prepared for the techniques of construction of compacted runways (Appendix C).

The characteristics of the snow surface may be extremely varied from site to site, but typical snow densities range from 0.3 to 0.5 Mg m<sup>-3</sup>, with little change in broad average density over several meters of depth. In addition there are tendencies for horizontal crusts and thin layers of harder or denser snow to occur at the current surface and at older surfaces at depth. These surface features have large horizontal dimensions in comparison to their thickness. The snow or crust hardness depends not only on the density but also on the temperature and the age-hardening (caused by sintering, which cements the snow grains together).

Obviously snow is not a conventional pavement or subgrade material. However, extensive testing has shown it to be quite suitable as a subgrade and as a base material for reworking to form a pavement. The technique of preparing an upper layer by disaggregation, compaction and rolling provides the basis for a two-layer system of upper pavement and lower subgrade which, it has been found, conforms adequately to the conventional two-layer approach of conventional flexible pavement design (Yoder 1959), provided appropriate design criteria are adhered to.

For wheeled vehicles, deep settling or bogging in soft snow is an obvious problem. A more serious problem occurs, however, when a wheel breaks through a surface crust. One would want to avoid the situation where a hard surface supports a wheeled vehicle to travel on in parts but, when the wheel does break through, deep settling in the softer snow below results in severe bogging.

This report aims to provide a concise summary of the techniques of design and testing for compacted-snow runways for wheeled aircraft. The techniques of pavement design and testing for compacted-snow pavements retain as much convention as possible and avoid the introduction of arbitrary tests. The results of detailed laboratory and field studies of snow in its natural and compacted states and the performance of a constructed trial strip pavement area at the Lanyon Junction site on Law Dome, near Casey, Antarctica, bring theory, research and practice into conjunction.

The detailed testing programs and analyses are given in Appendix A and Russell-Head et al. (1982, 1984).

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\* Modified slightly from a report published by the Melbourne University Programme in Antarctic Studies (Report No. 65, October 1984) written by D.S. Russell-Head, W.F. Budd and P.J. Moore.

## DESIGN OF A COMPACTED-SNOW PAVEMENT

### Outline of the method

The constructed pavement and the existing subgrade are viewed as a two-layer system (Fig. B1). Wheel settlements are calculated using Burmister's theory (Burmister 1943) of the elastic deformation of a two-layer system (Yoder 1959). The parameters required for the analysis are:

- Elastic modulus of pavement  $E_1$  and subgrade  $E_2$
- Poisson's ratio for pavement  $\nu_1$  and subgrade  $\nu_2$
- Tire pressure,  $p$
- Tire contact radius,  $a$  (assuming circular contact area)
- Pavement thickness,  $h$ .

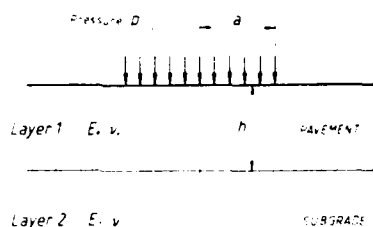


Figure B1. Diagram of a two-layer system with symbols of the design parameters. (After Poulos and Davis 1974.)

The elastic modulus is estimated from the CBR value (Russell-Head et al. 1982). If the CBR has not been directly measured, it may be estimated from the snow density, allowing for the time and temperature since compaction. Poisson's ratio is taken as being 0.35. The tire pressure is obtained from the aircraft manufacturer's specifications. The contact area is calculated from the ratio of the maximum weight of the aircraft to the tire pressure. The pavement thickness is usually the variable to be calculated from the others.

### Limitations of the method

There are a number of sources of potential error in the analysis. First, and perhaps most serious, is the general applicability of Burmister's elastic method to the real situation where nonlinear plastic deformations are developed. Second, the value of the effective elastic modulus for compacted snow, as derived from the CBR curves, may not be correct

at the larger scale of the tire and pavement. Third, Poisson's ratio for dense snow is not easily measured, and its use also assumes that deformations are elastic. However, Mellor (1964) described a viscous analog of Poisson's ratio (to draw a distinction between seismic elastic strains and visco-plastic deformation) and plotted data suggesting that a Poisson's ratio of 0.35 is reasonable for snow densities in the range 0.3 to 0.6 Mg m<sup>-3</sup>.

On the other hand, the agreement between the calculated and the measured settlement of a full-size plate loaded on a trial-construction snow pavement is close.

### Importance of preflight testing and proof rolling

The results of the design analysis should be viewed with caution and more as a guide to the behavior of the pavement and subgrade than as an exact model of the physical deformation process. The measurement and testing techniques described here are primarily to determine the snow properties before and after compaction as required for the design and performance characteristics of the strip.

After construction is completed, testing should be carried out by proof rolling using the wheels, tire pressures, undercarriage spacing and maximum load as appropriate for the aircraft using the strip. In other words, the proof roller should be an exact replica of the aircraft gear set loaded to the maximum gear set load.

The wheel settlement as a function of speed and resting time are important performance characteristics of the pavement. Settlement should be routinely monitored during the periods of aircraft use to ensure aircraft safety and to gain an accurate understanding of the factors that influence actual pavement performance.

IT IS ESSENTIAL THAT THE PAVEMENT IS TESTED BY FULL-SCALE PROOF ROLLING BEFORE AIRCRAFT ARE ALLOWED TO OPERATE.

### CBR of compacted snow

The CBR of compacted snow depends on its density, temperature and time after compaction. Age-hardening takes place more quickly at higher temperatures. A power-law relationship has been found (Russell-Head et al. 1984) to fit the fairly small data set of fully aged snow (Fig. B2):

$$CBR = 574 r^{5.4} \quad (B1)$$

for temperatures of -5 to -1°C, where CBR is in % and  $r$  is in Mg m<sup>-3</sup>.

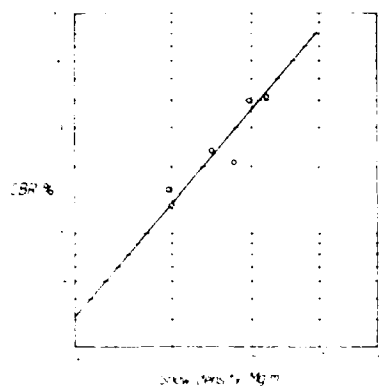


Figure B2. CBR value as a function of snow density for fully aged snow.

### Elastic modulus

An effective elastic modulus for snow can be calculated from a CBR test. The CBR test is analyzed as a loading on a finite layer over a rigid base. The settlement of the CBR piston, which has a diameter of 49.6 mm (1.954 in.) and an area of 1932 mm<sup>2</sup> (3.0 in.<sup>2</sup>), at a pressure equal to the tire pressure is used to calculate the elastic modulus. For a piston pressure of 0.66 MPa, corresponding to a tire pressure of 96 psi, a power-law relationship between CBR and effective modulus has been found (Russell-Head et al. 1982) (Fig. B3):

$$E = 0.81 \text{ CBR}^{1.67} \quad (\text{B2})$$

for temperatures of -10 to -1°C where  $E$  is in MPa and CBR is in %.

The effective modulus can be calculated directly from the snow density. From eq B1 and B2, substituting for CBR we obtain:

$$E = 3.28 \times 10^4 \rho^{9.02} \quad (\text{B3})$$

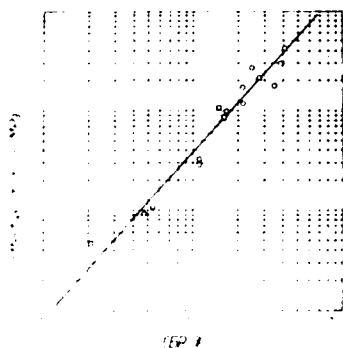


Figure B3. Effective elastic modulus of snow obtained from CBR test data.

(The constants in eq B1-B3 are given to three figures so that calculated values are consistent. It is not implied that the physical relationship is known to the same accuracy.)

### Settlement without pavement

Wheel settlements for the no-pavement situation can be calculated from the Boussinesq equation (Yoder 1959) which, for Poisson's ratio of 0.35, becomes:

$$w = 1.755 pa/E \quad (\text{B4})$$

where  $w$  = wheel settlement

$p$  = tire pressure

$a$  = contact radius

$E$  = effective modulus.

For a fully laden C-130H,  $p$  is 662 kPa and  $a$  is 288 mm.

Now using eq B3 to calculate  $E$ , settlement values can be plotted against snow density (Fig. B4).

### Purpose of the pavement

It is clear from Figure B4 that acceptably low pavement settlements would result from loading an existing surface if the snow densities were higher than about 0.45 Mg m<sup>-3</sup>. However, for aircraft use, some surface preparation generally would be

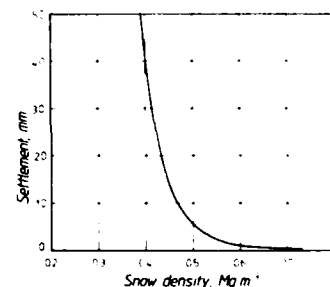


Figure B4. Settlement of C-130H on fully aged snow without a pavement.

needed to keep the surface roughness within acceptable limits. The bogging of aircraft wheels within soft, low-density zones is also a serious problem, and a pavement is the only means of ensuring that bogging cannot occur. In this situation the function of the pavement is to armor the subgrade.

### Settlement calculations and pavement design

#### Method for calculating pavement settlement

There are seven steps:

Step 1. Consult the manufacturer's data (e.g. Jane's *All the World's Aircraft*) to determine aircraft

parameters, and determine subgrade parameters from glaciological field data.

Step 2. Calculate pavement-thickness-to-contact-radius ratio for the range of pavement thickness, and calculate the pavement CBRs for  $E_1/E_2$  ratios of 2, 5, 10, 20 and 50 (eq B2).

Step 3. Read off a two-layer system chart the displacement factor corresponding to the  $h/a$  and  $E_1/E_2$  ratios. A chart in the form published by Thenn de Barros (1966) is easy to use.

Step 4. Calculate the settlements at the  $h/a$  and  $E_1/E_2$  ratios (eq B5).

Step 5. Plot the pavement-thickness-vs-settlement curves for the  $E_1/E_2$  ratios, and plot CBR vs settlement for constant pavement thickness.

Step 6. Read off values of pavement thickness for given settlement at the pavement CBRs corresponding to the  $E_1/E_2$  ratios. Read off values of CBR for a given settlement and and pavement thickness.

Step 7. Finally, plot a set of constant settlement curves within the domain of pavement thickness vs pavement CBR. In this convenient form, the combinations of CBR and thickness to achieve a given settlement are easily seen.

#### *Designing a pavement to give a specified settlement*

The next stage involves using the settlement chart to design a pavement of suitable strength and thickness. For a given specified settlement, there is a trade-off between pavement strength and thickness. In some instances, it may be easier to make a fairly thin pavement of high CBR. In other cases, where a high CBR is not feasible, a relatively thick pavement is needed.

At coastal sites where summer surface temperatures are near 0°C, it is fairly easy to achieve snow densities greater than 0.6 Mg m<sup>-3</sup>. Consequently, pavement CBRs greater than 40% are possible, so the pavement can be at a minimum thickness.

At inland sites the snow is cold and not easily compressed. Pending the results of actual compaction tests at an inland site, one can suggest that compacted-snow densities are not likely to be greater than about 0.5 Mg m<sup>-3</sup>, so the pavement CBRs are not likely to be greater than about 25%.

After determining the effective strength of the subgrade, the designer of the pavement needs to assess carefully the the settlement criterion in consultation with the aircraft operators, and then weigh

the advantages and disadvantages of making the pavement modestly strong but thick, or relatively thin but strong.

#### **Example design of airstrip for C-130 at Lanyon Junction**

##### *Step 1: Aircraft and subgrade parameters*

C-130H (Lockheed Model 382 Hercules) (Taylor 1982):

Maximum take-off weight = 70,310 kg = 690 kN

Landing gear = tricycle, tandem, four main wheels

Tire pressure,  $p = 662$  kPa

Contact radius,  $a = 288$  mm (calculated).

Subgrade at Lanyon Junction (Russell-Head et al. 1984):

Snow density = 0.48 Mg m<sup>-3</sup>

(The natural snow at Lanyon Junction has a layered stratigraphic structure. Typically, ice layers of 0.8 Mg m<sup>-3</sup> density and a couple of centimeters thick alternate with 5- to 10-cm layers of firn with density of 0.43 Mg m<sup>-3</sup>. The average density is about 0.48 Mg m<sup>-3</sup>.)

CBR = 11% (10.8% calculated)

(The CBR of the subgrade, estimated from its average density, is 11%. Because of the layered structure, it is not possible to measure the average effective CBR of the subgrade directly. Measured values ranged from 11 to 70%.)

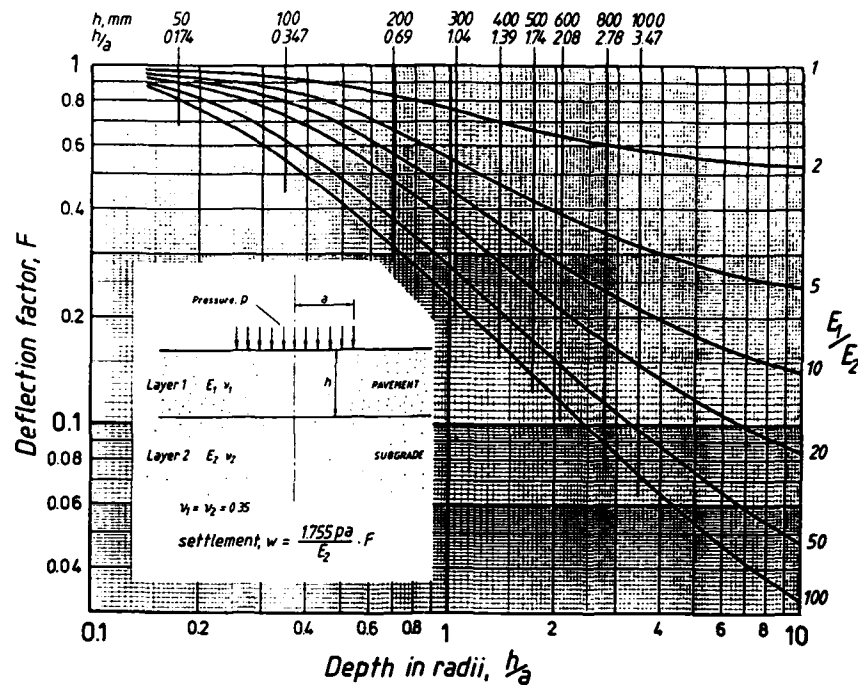
$E = 44$  MPa (43.7 MPa calculated).

##### *Step 2: Ratio of pavement thickness to contact radius, and pavement CBR values*

| Contact radius<br>= 288 mm |       | Subgrade modulus, $E_2 = 43.7$ MPa |             |                  |
|----------------------------|-------|------------------------------------|-------------|------------------|
| $h$ (mm)                   | $h/a$ | $E_1/E_2$                          | $E_1$ (MPa) | CBR <sub>1</sub> |
| 50                         | 0.174 | 2                                  | 87.4        | 16.5             |
| 100                        | 0.347 | 5                                  | 218.5       | 28.6             |
| 200                        | 0.69  | 10                                 | 437         | 43.2             |
| 300                        | 1.04  | 20                                 | 874         | 65.5             |
| 400                        | 1.39  | 50                                 | 2185        | 113              |
| 500                        | 1.74  |                                    |             |                  |
| 600                        | 2.08  |                                    |             |                  |
| 800                        | 2.78  |                                    |             |                  |
| 1000                       | 3.47  |                                    |             |                  |



Step 3: Displacement factors for  $h/a$  and  $E_1/E_2$  ratios



| h<br>(mm) | h/a   | F for $E_1/E_2$ of |       |       |       |       |
|-----------|-------|--------------------|-------|-------|-------|-------|
|           |       | 2                  | 5     | 10    | 20    | 50    |
| 50        | 0.174 | 0.97               | 0.94  | 0.93  | 0.89  | 0.84  |
| 100       | 0.347 | 0.92               | 0.84  | 0.79  | 0.72  | 0.62  |
| 200       | 0.69  | 0.82               | 0.66  | 0.57  | 0.48  | 0.375 |
| 300       | 1.04  | 0.74               | 0.54  | 0.435 | 0.355 | 0.265 |
| 400       | 1.39  | 0.69               | 0.47  | 0.36  | 0.285 | 0.205 |
| 500       | 1.74  | 0.66               | 0.42  | 0.31  | 0.24  | 0.175 |
| 600       | 2.08  | 0.64               | 0.385 | 0.28  | 0.21  | 0.15  |
| 800       | 2.78  | 0.60               | 0.34  | 0.235 | 0.17  | 0.115 |
| 1000      | 3.47  | 0.585              | 0.31  | 0.21  | 0.145 | 0.097 |

Figure B5. Two-layer system influence chart.

Step 4: Calculate settlements

settlement,  $w = f(1.755 p a, E_2) \cdot F$  (B5)

| h<br>(mm) | w (mm) for CBR of |      |      |      |      |
|-----------|-------------------|------|------|------|------|
|           | 16.5              | 28.6 | 43.2 | 65.5 | 113  |
| 50        | 7.43              | 7.20 | 7.12 | 6.81 | 6.43 |
| 100       | 7.04              | 6.43 | 6.05 | 5.51 | 4.75 |
| 200       | 6.28              | 5.05 | 4.36 | 3.68 | 2.87 |
| 300       | 5.67              | 4.13 | 3.33 | 2.72 | 2.03 |
| 400       | 5.28              | 3.60 | 2.76 | 2.18 | 1.57 |
| 500       | 5.05              | 3.22 | 2.37 | 1.84 | 1.34 |
| 600       | 4.90              | 2.95 | 2.14 | 1.61 | 1.15 |
| 800       | 4.59              | 2.60 | 1.80 | 1.30 | 0.88 |
| 1000      | 4.48              | 2.37 | 1.61 | 1.11 | 0.74 |

Step 5: Curves of settlement vs pavement thickness at constant pavement CBR and settlement vs pavement CBR at constant pavement thickness

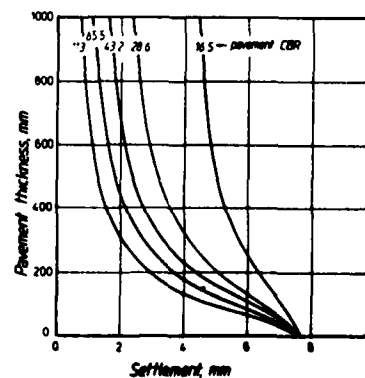


Figure B6. Settlement vs pavement thickness at constant pavement CBR.

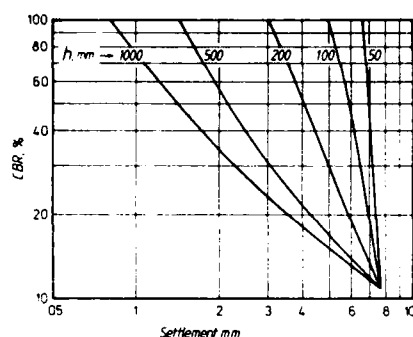


Figure B7. Settlement vs pavement CBR at constant pavement thickness.

Step 6: Determine pavement thickness for given settlement and CBR, and CBR for given settlement and pavement thickness

| w<br>(mm) | h (mm) for CBR of |      |      |      |     |
|-----------|-------------------|------|------|------|-----|
|           | 16.5              | 28.6 | 43.2 | 65.5 | 113 |
| 1         |                   |      |      |      | 640 |
| 1.5       |                   |      |      | 670  | 420 |
| 2         |                   |      | 670  | 440  | 305 |
| 3         |                   | 565  | 350  | 260  | 190 |
| 4         |                   | 320  | 230  | 175  | 130 |
| 5         | 505               | 210  | 155  | 120  | 90  |
| 6         | 245               | 130  | 105  | 85   | 65  |
| 7         | 110               | 65   | 55   | 40   | 30  |

| w<br>(mm) | CBR for h(mm) of |      |      |
|-----------|------------------|------|------|
|           | 200              | 500  | 1000 |
| 1         |                  |      | 75   |
| 1.5       |                  |      | 46.5 |
| 2         |                  |      | 33.5 |
| 3         |                  |      | 23   |
| 4         |                  |      | 18   |
| 5         |                  |      | 15   |
| 6         |                  | 14.2 | 13.2 |
| 7         | 13.2             | 12.0 | 11.6 |

Step 7: Plot pavement settlement curves

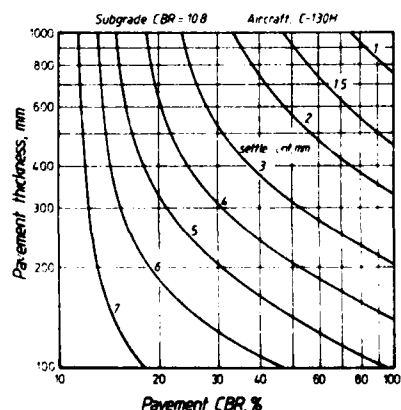


Figure B8. Pavement thickness vs pavement CBR for different settlements.

### Design of pavement for C-130 at Lanyon Junction

It is clear from the settlement values that a pavement is not needed if 10-mm wheel ruts are acceptable. The primary purpose of constructing a pavement is to prevent the aircraft wheels from encountering loose subgrade material. The pavement is used more as a protective device than as a large-scale load-bearing structure.

The pavement needs to be constructed and tested so that there is a continuous surface that is impenetrable to the aircraft wheels. The pavement quality and thickness required to perform the strength function are modest:

Minimum thickness = 300 mm

Minimum CBR = 20%.

The more difficult task is to ensure that the pavement is absolutely continuous throughout the runway, taxiway and apron. Testing and quality control must be integral to the construction program.

### Application to other aircraft and other sites

The design process can be applied to other aircraft if landing gear details and maximum aircraft mass are known. Table B1 contains a listing of the details of transport aircraft that are used or may have a use in Antarctica. The design calculations use the tire pressure and the radius of the tire contact area. These values are shown in the list. The tire pressure can be altered to suit the runway conditions. The tire contact radius listed is for maximum aircraft weight and maximum tire pressure.

For application to other sites, the CBR of the runway site is required to obtain an effective modulus value. The CBR is strongly dependent on snow density but is also a function of the age and temperature of the snow and probably the grain structure as well. The site needs to be investigated to accurately determine the CBR and  $E$  values.

There appears to be a more direct relationship between average rammsonde hardness ( $R$ ) and CBR than between either  $R$  or CBR and snow density. The rammsonde instrument has had wide use over many years by glaciologists, so rammsonde profiles have been published for many areas in Antarctica. It may prove useful to use the rammsonde values to estimate the local minimum CBR value and hence make a preliminary design before the site investigations.

**Table B1: Aircraft data. (From various editions of *Jane's All the World's Aircraft*).**

|  | <i>Ilyushin<br/>18D</i>       | <i>Lockheed<br/>C-130</i>   | <i>Lockheed<br/>C-141</i>     | <i>Ilyushin<br/>76T</i>             | <i>Boeing<br/>747 Combi*</i>   |
|--|-------------------------------|-----------------------------|-------------------------------|-------------------------------------|--------------------------------|
| Max take-off mass (kg)                     | 64,000                        | 70,310                      | 146,555                       | 170,000                             | 360,000                        |
| Main landing gear                          | 8 wheels, 2<br>4-wheel bogies | 4 wheels, 2<br>tandem units | 8 wheels, 2<br>4-wheel bogies | 16 wheels, 2 sets<br>of 2 rows of 4 | 16 wheels, 4<br>4-wheel bogies |
| Main tire size (mm)<br>(in.)               | 930 x 305<br>36.5 x 12        | 1422 x 508<br>56 x 20       | 1118 x 406<br>44 x 16         | 1300 x 480<br>51 x 19               | 1245 x 483<br>49 x 19          |
| Tire pressure (bar) <sup>†</sup><br>(psi)  | 7.9<br>114                    | 6.6<br>96                   | 12.4<br>180                   | 5.0<br>73                           | 13.5<br>195                    |
| Contact area<br>per tire (m <sup>2</sup> ) | 0.100                         | 0.260                       | 0.145                         | 0.208                               | 0.164                          |
| Equivalent radius (mm)                     | 178                           | 288                         | 215                           | 258                                 | 228                            |
| Max payload (kg)                           | 13,500                        | 19,685                      | 32,025                        | 40,000                              | 72,000                         |
| Cruising speed (knots)                     | 337-364                       | 300-325                     | 430-492                       | 405-432                             | 500                            |
| Take-off roll (m)                          | 1300                          | 1091                        | 1300                          | 850                                 | 2500                           |
| Landing distance (m)**                     | 850                           | 518                         | 850                           | 450                                 | 2000                           |
| Range with max<br>payload (km)             | 1997                          | 2160                        | 2550                          | 2700                                | 5500                           |
| Ferry range (km)                           | 3500                          | 4100                        | 5550                          | 3508                                | 6800                           |

\* Specifications of 747 Combi depend on engine type. Representative values are given here.

<sup>†</sup> Tire pressures are usually varied to suit aircraft load and runway conditions. For some aircraft, notably C-130 and 76T, tire pressures can be adjusted in flight.

\*\* Operational data are given here as a guide for comparison of aircraft capabilities. The values are only nominal. Actual values will depend on the specific situation such as local runway and meteorological conditions.

Suggested relationships between rammsonde hardness, CBR and effective modulus are:

$$CBR = 1.68 R^{0.432} \quad (B6)$$

$$E = 0.81 CBR^{1.67} \quad (B7)$$

where  $R$  is in kg, CBR is in % and  $E$  is in MPa.

Equations B6 and B7 can be rearranged to give the effective modulus ( $E$ ) directly from rammsonde hardness ( $R$ ):

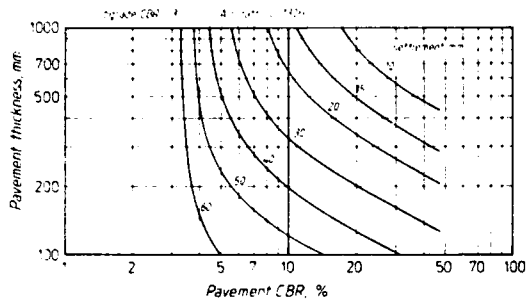
$$E = 1.93 R^{0.721} \quad (B8)$$

(These relationships apply for CBR tests where the piston speed is 1 mm per minute. The standard piston speed used in the United States is 0.1 inch per minute, which will give probably about a 10% higher CBR value for the same snow tested at 1 mm per minute.)

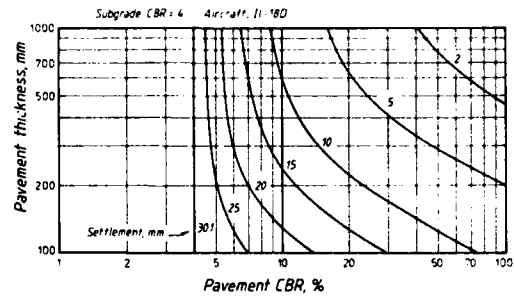
Figure B9 contains settlement charts for C-130H for subgrades of 3, 4, 6 and 10 CBR, and also charts for IL-18D, C-141B, IL-76T and 747 Combi for a subgrade of 4. There are also two charts that compare the aircraft pavement requirements for common settlements of 10 mm and 20 mm.

#### Estimate of subgrade CBR at inland sites, including the South Pole

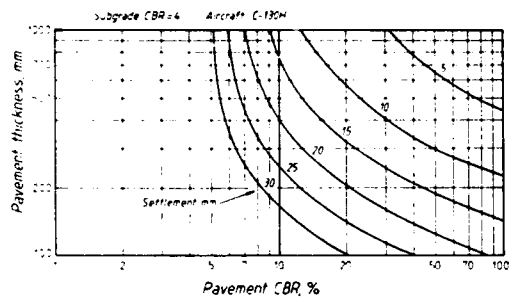
The CBR value of snow depends on its density, temperature, grain structure and thermal and mechanical history. The snow density is the most important parameter. Temperature has a small effect on CBR. However, the temperature at the South Pole is so low that the effect on CBR could be significant in comparison to the CBR of snow of the same density and structure at a coastal Antarctic site. (It may be that the elevation may also have an influence on CBR as the air pressure will affect the vapor transport within the firm.)



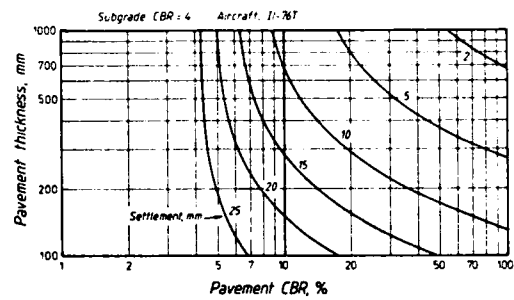
a. C-130H with  $CBR_{sub} = 3$ .



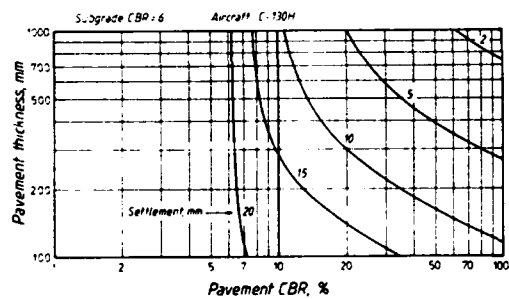
e. IL-18D with  $CBR_{sub} = 4$ .



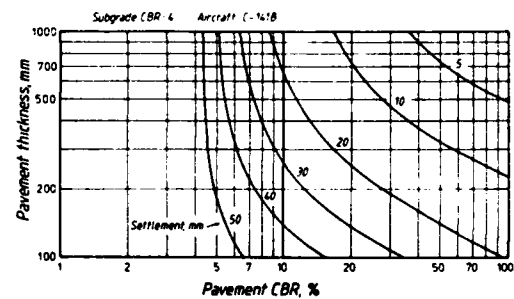
b. C-130H with  $CBR_{sub} = 4$ .



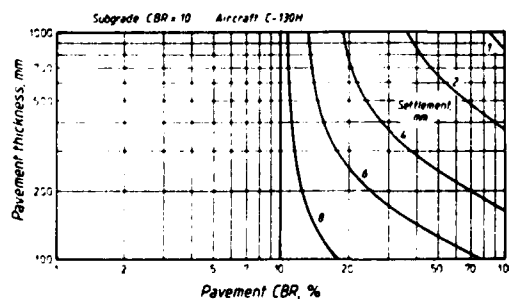
f. IL-76T with  $CBR_{sub} = 4$ .



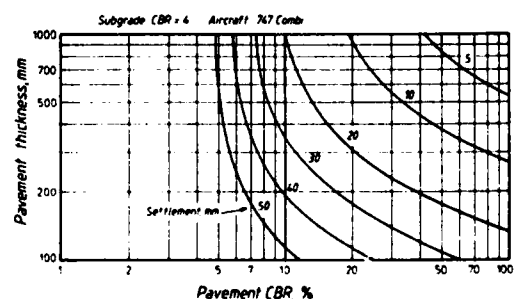
c. C-130H with  $CBR_{sub} = 6$ .



g. C-141B with  $CBR_{sub} = 4$ .

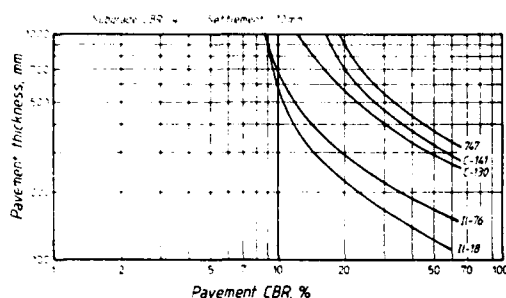


d. C-130H with  $CBR_{sub} = 10$ .

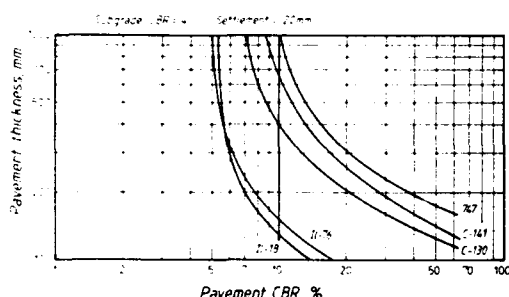


h. 747 Combi with  $CBR_{sub} = 4$ .

Figure B9. Settlement charts for various aircraft and various CBRs.



i. Pavement requirements for aircraft at 10-mm settlement with  $CBR_{sub} = 4$ .



j. Pavement requirements for aircraft at 20-mm settlement with  $CBR_{sub} = 4$ .

Figure B9 (cont'd). Settlement charts for various aircraft and various CBRs.

The density at the South Pole is known, but the relationship between CBR and density for South Pole snow is not known. One could expect that snow would be stronger, as measured by a CBR test, at lower temperatures. Now, a relationship between CBR and rammsonde hardness has been found for comparatively warm snow ( $-1^{\circ}\text{C}$  to  $-10^{\circ}\text{C}$ ) (Russell-Head et al. 1984). If this relationship held for cold snow (e.g. at  $-50^{\circ}\text{C}$ ), the CBR could be calculated from the appropriate rammsonde number. Now the argument shifts to finding the appropriate rammsonde hardness value. It seems best to solve this by trying to find a relationship between density and rammsonde hardness for South Pole snow, and then estimating the hardness number for the average snow density at the surface at the South Pole.

Kojima (1964) gives the average surface density at the South Pole as  $0.36 \text{ Mg m}^{-3}$ . He estimates this surface density from a least-square linear regression of the snow density and depth data gathered from pit studies.

Density and rammsonde profiles in the Byrd and South Pole areas have been published (Koener

1964, Taylor 1964, Benson 1970). It is possible to match rammsonde hardness with density where both the density and the rammsonde values are constant. There are usually only few occasions where this occurs in a given profile.

Figure B10 is a plot of the data estimated from the published profiles. Both the Byrd and South Pole snow exhibit higher rammsonde hardness than snow of the same density in the Casey runway area (Russell-Head et al. 1984). Although the South Pole mean temperature (about  $-50^{\circ}\text{C}$ ) is lower than that for the Byrd area (about  $-29^{\circ}\text{C}$ ), the Byrd area snow is harder than the South Pole snow.

It seems that the appropriate rammsonde hardness to be ascribed to surface snow of  $0.36 \text{ Mg m}^{-3}$  is about 10 kg (Fig. B10).

If the relationship between rammsonde hardness and CBR found for snow in the Casey runway area holds for South Pole snow, then for CBR in percent and  $R$  in kilograms:

$$CBR = 1.68 R^{0.432}$$

$$= 1.68 10^{0.432}$$

$$= 4.5\%$$

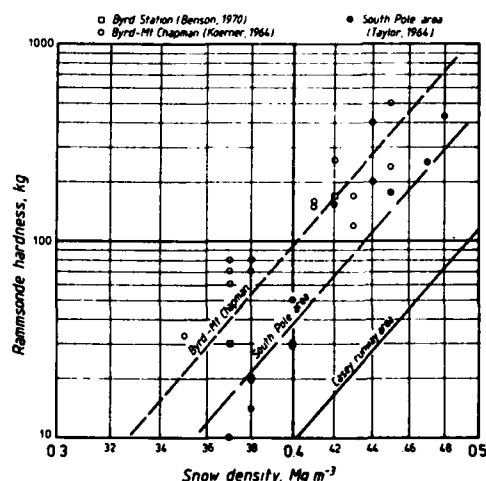


Figure B10. Rammsonde hardness vs density for snow in the Byrd station area, in the South Pole area and at the Casey runway site.

## PAVEMENT TESTING METHODS

The basic approach to testing is to use the most appropriate method to investigate the problem at hand. Rammsonde profiling is a fairly quick and easy way to check over an area. CBR tests are fairly

time consuming but give a direct measure of the strength of the snow. Plate bearing tests are very time consuming but give a direct indication of the creep response of the pavement. Proof rolling can only be done after the pavement has been constructed, but it is the ultimate quality control test.

#### **On-site laboratory**

A portable coldroom, with a temperature control from  $-2$  to  $-20^{\circ}\text{C}$ , is needed on-site. The measurements of snow density, particle size distribution and CBR are all to be done under controlled laboratory conditions.

#### **Density measurement**

Snow samples can be taken from the field by coring or cutting out a slab of snow. Samples can be prepared in the cold laboratory with a band saw or other cutting tool. Linear measurements are to be made with calipers, and the mass determined by a digital read-out laboratory balance.

#### **Particle size distribution**

Snow samples can be disaggregated by hand crushing and rubbing snow against snow. A set of sieves are placed in a shaker machine which is set to run for a standard time. The sieves are then individually weighed with the laboratory balance, and the particle size distribution can be determined in the usual way.

#### **Temperature measurement**

Field measurements can be made with platinum-element thermometers or with calibrated thermistors. The thermistors have the advantage of low thermal mass and short response time. The platinum-element thermometers are simpler to calibrate. Mercury-in-glass and alcohol-in-glass thermometers are useful in the coldroom but require careful radiation shielding in the field to obtain correct snow temperatures.

#### **Rammsonde profiling**

The standard Swiss rammsonde is a very useful instrument to check on snow properties at depth (Bull 1956). The standard 40-mm-diameter tip size is good for low- and medium-density snow. A smaller 20-mm tip of the same geometry as the standard tip should be used for the stronger pavement snow. An accurate correlation between the standard and 20-mm tip should be determined on-site.

The rammsonde can be used in the initial site investigation and also during pavement construction to check on pavement thickness and strength.

The rammsonde hardness can be used as an indicator of density changes (Fig. B10) and, more importantly, as a direct indicator of CBR through eq B6.

#### **CBR tests**

Samples for CBR tests need to cut out as slabs or cored with a special-purpose large-diameter auger. Samples from the field need to be handled carefully prior to testing to retain their in situ characteristics. All CBR tests should be performed in the cold laboratory in a testing machine.

Field experience has shown that the in situ testing of firm is not practical (Russell-Head et al. 1984), mainly because of thermal disequilibrium between the piston and snow and also difficulties in ensuring that the displacement reference is rigid and stable. Apart from the instrument difficulties, the in situ CBR method entails a heavy logistic and time overhead. Laboratory testing is more satisfactory on many counts.

#### **Plate bearing tests**

Test plates of the same size as the tire contact area can be used to load hard-standing pavement. The short-term and long-term creep settlement behavior can be assessed with the plate bearing test. Construction equipment (for example, tractors) can provide the dead weight loads. A large-diameter hydraulic ram can be used to jack up the load.

Displacement measurements need to be made carefully. A long, rigid reference bar needs to be fixed to the snow outside the area being deformed. An automatic data acquisition system is needed to give a continuous read-out of the settlement. The resulting settlement-time graph provides the information required. Manual reading of a dial gauge is useful for checking purposes, but it is not suitable for obtaining an accurate settlement-time relationship.

#### **Proof rolling**

A replica of a main landing gear unit for the aircraft to be used on the runway needs to be constructed within a load trailer. The load trailer should be designed so that dead weight can be readily loaded on and off. The maximum load should correspond to the maximum aircraft gear load. A proof roller so constructed can be towed by a tractor (e.g. Caterpillar D7). The whole length of the runway can be tested within an hour. A number of passes can be made at suitable spacings across the width of the runway pavement. The whole runway and taxiway areas can be thoroughly checked in this way. Any pavement defects that

come to light by proof rolling can be investigated and rectified. The repaired area can be then tested again.

Proof rolling is the quality acceptance test. If the proof roller is a replica of the aircraft gear and gear load, and if the proof roller is used to check all the pavement, then there is no risk in allowing aircraft to operate on the pavement. Aircraft should not be allowed to operate if the pavement areas have not passed the replica proof rolling test.

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## APPENDIX C: A CONSTRUCTION MANUAL FOR COMPACTED-SNOW RUNWAYS\*

### SUMMARY

This manual is a guide to the construction of snow runway pavements for use by heavy wheeled aircraft in Antarctica. Its purpose is to summarize a construction technique based on the overconsolidation of the pavement snow by a heavy, multi-tired pneumatic roller.

Quality control is an important issue for construction work in Antarctic field conditions, and the simplicity of compaction by a towed roller offers a degree of inherent quality control absent from more specialized methods of increasing the strength of the existing snow. Because snow runways will generally be constructed in areas of net annual snow accumulation, the construction program is really a prelude to a continuing yearly maintenance program. It is important that the construction technique be capable of adaption to a simple and reliable maintenance program. The towed heavy roller technique is well suited for routine maintenance.

Basic designs of a 160-tonne 1-MPa multi-tired compaction roller and a 75-tonne C-130 proof roller are given. Their use in the construction program is discussed in detail. The ancillary equipment and basic logistic support required for a construction program are also discussed.

### BACKGROUND

#### Brief history of compressed-snow runways in Antarctica

The U.S. Navy constructed the first recorded compacted-snow runway in Antarctica in 1947 on the Ross Ice Shelf (Barthelemy 1975). Subsequent U.S. experience during the 1960s showed that it was possible to densify snow by disaggregation with pulvimixers or snow millers, and that higher densities result from using rollers on the disaggregated snow. Pavements were produced that supported C-130 aircraft (Moser and Sherwood 1967, Abele et al. 1968). The successful introduction of ski-equipped C-130 aircraft to Antarctica curtailed

further U.S. work on compressed-snow runways for heavy wheeled aircraft.

At Molodezhnaya, Soviet experiments with conventional multi-tired rollers were started in the mid-1960s. During the 1970s a trial runway pavement of high-density snow was produced, and testing showed it capable of supporting heavy wheeled aircraft (Aver'yanov et al. 1975). A runway was completed in 1980 and has been used for regular summer flights by Ilyushin 18D aircraft. In 1986 an Ilyushin 76T aircraft used compressed-snow runways at Molodezhnaya and Novolazarevskaya (Antarctic 1986).

In the 1983-84 summer season, a trial construction of a compressed snow pavement near Casey by an Australian team showed that a strong pavement could be made by using heavy multi-tired rollers to compress snow disaggregated by a snow miller (Russell-Head et al. 1984). A full-scale plate bearing test showed that the trial pavement would adequately support C-130H wheel loads.

#### Purpose of manual

This manual aims to guide the potential constructor of a compressed snow runway in Antarctica towards the production of a sound pavement by a method incorporating quality control and based on sound engineering principles.

Advanced techniques requiring the input of heat, water, sawdust or polystyrene are not amenable to large-scale pavement production. Achieving adequate quality control under Antarctic field conditions is likely to be difficult. An additional disadvantage of construction methods which require the importation of a substance to be incorporated into a pavement is that additional material will be needed each year.

The basic method promoted here is to overconsolidate the pavement material by using a multi-tired pneumatic roller which can progressively produce settlement, and therefore compaction, until multiple passes at the highest mass and tire pressure cease to produce a useful permanent settlement. The tire size, tire spacing and maximum tire pressure of the compacting roller are selected so that the roller can impose a higher loading on the pavement than aircraft gear loading, when the tire contact geometries and tire pressures are taken into account.

This method of compaction has built-in quality control because it amounts to a continual testing of the pavement. As the compaction roller is drawn

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\* Modified slightly from a report published by the Melbourne University Programme in Antarctic Studies (Report No. 67, November 1987) written by D.S. Russell-Head, W.F. Budd and P.J. Moore.



over the pavement material, it compacts without the need to directly handle the pavement material. The rolling operation is simple to manage because it is easy to see where it has been. Furthermore if there is any doubt about the number of coverages received by a particular area, extra coverages can be made without any special preparation of the pavement or equipment.

## PAVEMENT DESIGN SPECIFICATIONS

The design of snow pavements is covered in Appendix B. The constructor needs to understand the principles of the design process in order to assess the best method of achieving the desired result.

The main input parameters to the pavement design are the aircraft gear loads and tire pressures and the subgrade quality. A pavement of the required performance has to be constructed with the existing snow surface under prevailing meteorological conditions, and there will probably be a number of ways of going about the task.

One major decision is to settle on the pavement thickness and strength. There is a tradeoff between thickness and strength, and a pilot field test with actual construction equipment needs to be undertaken to find out what snow densities and strengths can be routinely achieved.

Should substantial additional thickness be required, it is likely that the best method of achieving it will be by compaction over several summer

seasons. For a runway of 3,000 x 80 m, 100 mm of loose snow on the pavement represents a volume of 24,000 m<sup>3</sup> and, for a snow density of 0.4 Mg m<sup>-3</sup>, a mass of 9,600 tonnes. It is not an easy task to spread this amount of snow under Antarctic field conditions with acceptable quality control. The construction of transverse snow berms to act as snow fences may prove a useful method of collecting additional wind-blown snow onto a pavement during a single summer construction period.

## SITE INVESTIGATION

### Meteorological and glaciological conditions

It is important to avoid sites where melt pools could form in summer, and the meteorological records should be consulted to check on the maximum summer temperatures. The local firm carries with it a record of past events, and a stratigraphic study in the site area will show evidence of the extent of summer melting. Ice lens formation is widespread in Antarctica and does not necessarily indicate excessive melt. The acceptable limit of melt may be about 20% of ice by volume, e.g. solid clear lenses of about 25 mm thick with only 100 mm between melt layers.

Meteorological records also need to be examined to find the direction of the strongest winds, as the runway alignment will usually be in this direction. The wind record will also reveal the likely conditions during the planned construction period.

### Site survey

A topographic map of the general area of the proposed site needs to be available before the final location is settled. Sufficient detail can be obtained by taking levels at 1-km grid spacings in a 10- x 10-km area with a level accuracy of 0.5 m.

The runway site itself then needs to be surveyed. The centerline should be leveled at say 250-m intervals to 0.1 m. At the 250-m stations the transverse slope should be determined by taking levels at say 50 m and 100 m from the runway centerline.

The longitudinal and transverse slopes (Fig. C1) need to be within the requirements of the

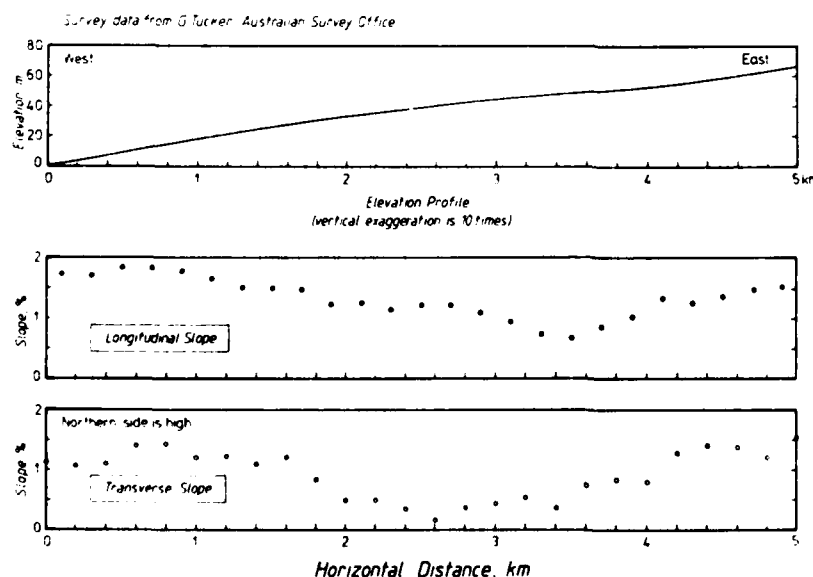


Figure C1. Site survey of proposed Casey runway.

aircraft. The size of the runway and apron areas are also determined by the type of aircraft to be used. In view of some of the difficulties of aircraft operation in Antarctica (e.g. high winds, white-out), a longer and wider runway than normal is indicated. Generally, if a compacted-snow runway is well sited, there is little restriction in providing extra length and width except for the added time to produce it. For C-130 use, a runway pavement of 3000 m in length and 80 m in width seems appropriate. The area of the apron needs to be about 10,000 m<sup>2</sup> to accommodate two C-130 aircraft.

### SITE TESTING PROGRAM

The existing subgrade quality has a substantial influence on the magnitude of the construction effort. It is very important that a thorough site investigation be undertaken prior to construction. The investigation team needs to be conversant with previous glaciological work but must obtain at first hand their own field data on the engineering properties of the snow at the site. A field laboratory coldroom is needed for the site investigation.

The centerline of the runway site should be sampled every 500 m for snow density, particle size distribution, rammsonde hardness profile and California Bearing Ratio (CBR). Stratigraphy pits should be dug to 2 m at every kilometer along the strip site.

Instrumentation should be set up to monitor air temperature, snow temperature profile, incoming radiation, and wind speed and direction. These measurements should continue throughout the construction period, as they will allow interpretation and prediction of equipment performance.

### COMPACTION PROPERTIES OF SNOW

Field testing has shown that snow densities of greater than 0.7 Mg m<sup>-3</sup> can be achieved by pneumatic-tired rollers when working with moist snow (Aver'yanov et al. 1975, Russell-Head et al. 1894). Laboratory work indicates that dry snow can be compacted to densities greater than 0.55 Mg m<sup>-3</sup> at a pressure of 1 MPa. Figure 12 shows the effect of temperature on the compacted density. The compaction process is much more efficient for temperatures above -1°C than for snow temperatures in the -10 to -5°C range. Clearly there is a construction advantage in working the snow at its highest temperature.

## CONSTRUCTION PROCEDURES

### Disaggregation

Initially the top 300 mm of snow should be disaggregated before the compaction work is started. Ice lenses need to be broken up and mixed with granular firm to make a reasonably uniform mix ready for compaction.

Snow millers are excellent disaggregators but suffer the disadvantage of removing the material from its original place. This means that a material transfer process has to be controlled, and this is where a serious quality control problem can emerge. It can be difficult to keep track of where the miller has been—especially after a blizzard—and areas can be missed.

A simple twin-gang multiple-disk plow can chop up the ice lenses but does not achieve the excellent quality of the material produced by the snow miller. Nonetheless the disk plow will mix the surface material adequately, and it is much quicker and easier to control than the miller operation. To work the surface material to a depth of 300 mm, the disk diameter needs to be 900–1000 mm.

### Compaction

The compaction device is a heavy, towed multi-tired pneumatic roller (Fig. 13, Table C1). It is articulated and has a turning radius of about 20 m.

Table C1. Compaction roller specifications.

|                       |   |
|-----------------------|---|
| <b>ROLLER TYPE</b>    | Towed multi-tire pneumatic  |
| <b>TIRES</b>          |   |
| Type                  | Smooth compactor type   |
| Size                  | 13.00 x 24 - 26 ply   |
| Pressure              | 1000 kPa max  |
| Number                | Two rows of 10  |
| <b>AIR SYSTEM</b>     |   |
| Type                  | Through axle supply   |
| Control               | Regulator to each axle pair                                       |
| Range                 | 100 to 1000 kPa   |
| <b>WEIGHTS:</b>       |   |
| Empty                 | 40,000 kg   |
| Fully laden           | 160,000 kg  |
| Load weights          | 2,500 kg stackable  |
| Load handling         | Fork lift   |
| <b>DIMENSIONS:</b>    |   |
| Roll width            | 4 m approximately   |
| Turning circle        | 20 m maximum  |
| Tire spacing          | 100 mm maximum  |
| Tire offset           | 100 mm approximately  |
| Wheel base            | 7 m   |
| Overall width         | 1.6 m   |
| Length ex drawbar     | 8.2 m   |
| Length overall        | 11.2 m  |
| <b>TRANSPORTATION</b> | Disassembles into <10 tonne parts<br>Parts transportable by C-130 |

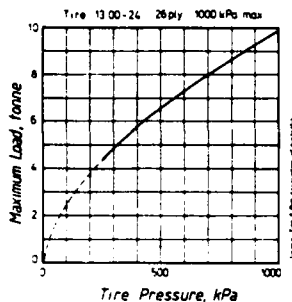


Figure C2. Maximum rated load for a given inflation pressure for a smooth tread 13.00 x 24 compaction tire.

Tire pressures can be adjusted to each pair of wheels individually. Dead weights of 2.5 tonnes are fabricated from steel and are designed to be handled by a 943 LGP tracked loader fitted with lifting forks. The roller is designed to be pulled by a D7 LGP tractor. The empty weight of the roller is 40 tonnes, and the maximum weight is 160 tonnes. There are 20 tires in two rows of 10. The trailing half of the roller is offset with respect to the first half so that the tire ruts overlap.

The use of the roller can be explained by referring to Figures C2 and 14. Figure C2 shows the maximum allowable tire load for a given tire pressure. Initially the roller will be unladen and the wheel load will be 2 tonnes (Fig. 14, stage one). The minimum tire pressure allowed is about 125 kPa (18 psi). This low pressure permits the roller to be towed to the site without bogging and to start off the compaction of the loose disaggregated snow.

The idea is to achieve the maximum compaction within the capability of the drawbar pull of the tractor. A D7 LGP tractor has a mass of about 23.5 tonnes and will be able to pull on disturbed snow with about 4 tonnes of force and on firm snow with about 6 tonnes of force. In second gear a drawbar force of about 7 tonnes is available up to 5 kph. The likely travel speed with the roller is in the 3- to 5-kph range.

The least traction is available at the first coverage of the disaggregated snow, and it will probably pay to use the roller unloaded for the first coverage. The width of the tire cover is 4 m and so, allowing for a 20% overlap on each pass; about 25 passes are needed to cover the width of an 80-m-wide pavement. Four to five roller wheel passes are needed at constant roller conditions before the surface is evenly compacted. For the compaction roller with two rows of closely spaced tires, two or perhaps three passes may be needed before increasing the load and tire pressure. The time to cover a 80-m x 3-

km runway twice at a speed of 4 kph is about 38 hours.

Load increments of 40 tonnes (2 tonnes per wheel) would seem to give a good balance between drawbar pull and number of load changes (and hence coverages). Therefore, the roller could be used in five stages (Fig. 14). The first four stages see an increase in tire loads from two to eight tonnes, and stage five involves a tire pressure change from 700 to 1000 kPa. The total pavement rolling time is estimated to be 190 hours (five stages at 38 hours).

On-site experience will guide the constructor as to the best compaction program, and a small area, say 20 m x 300 m, should be used as a pilot test before starting the main runway work. The time taken to do the test is small in comparison to the savings that could be made on the full-scale job.

### Leveling

A conventional road grader (Caterpillar 14G) fitted with laser leveling equipment has been used successfully in the field (Russell-Head et al. 1984). It is best for the grader to work on compacted snow, so it could be used on stage 2 material. The 14G has a standard blade width of 4.27 m and is capable of operating at a higher speed than the towed roller.

The determination of the best-fit grade to the compacted surface is a full-time operation for a surveying team, and a procedure will need to be worked out for operating the grader to achieve the desired grade.

### Chaining

Small-scale smoothing of the runway can be achieved by dragging a large chain behind two tractors traveling along the edges of the runway. The loads are not large, and smaller tractors, e.g. D5s, could be used. The chain needs to be about 75-mm anchor chain. (The diameter of the link material is 75 mm, the link itself being about 230 mm wide by about 380 mm long.) The chain length needs to be about twice the distance between the towing tractors.

Chaining is likely to be very useful in smoothing out the runway after snow deposition from a blizzard. Both the construction and maintenance programs will probably find use for chaining.

## PAVEMENT TESTS

### Indicative tests

Rammsonde profiling is a very simple and quick method of checking the uniformity and thickness of the pavement. It also gives an indication of the

pavement density and strength. Should a problem area present itself during heavy rolling or proof rolling, the rammsonde can be used to quickly determine the extent of the fault.

Density measurements on test core samples from the pavement are more time consuming than rammsonde testing but give a direct measurement of the density of the compacted snow. The efficiency of the compaction program can be gauged with regular density measurements. The pavement strength is strongly dependent upon density, and accurate density measurements can be used to estimate CBR values.

California Bearing Ratio (CBR) tests require careful attention to sample preparation, testing procedure and interpretation. The tests must be performed in a reliable testing machine under controlled conditions in an on-site coldroom to achieve reproducible results.

Plate bearing tests will be useful in assessing the longer-term creep settlement of the apron area. A continuous read-out of settlement over a 7-day period will give a good indication of the settlement-time relationship for a fully laden aircraft. (A fully laden aircraft may have to be left standing if an aircraft malfunction prevents take-off and a blizzard arrives during the repair time.)

### Proof rolling

A proof roller with the same tires and layout as that of the main gear of the aircraft needs to be available for checking the adequacy of the runway pavement. Figure 16 shows a proof roller for C-130 aircraft. It is designed to be taken apart for transportation by C-130 aircraft and uses the same steel dead weights and loading system as for the compaction roller (Table C2). The maximum design load is 75 tonnes, which is 6.5% greater than the maximum allowable aircraft load.

After the pavement has been produced and is ready for final testing, the proof roller is loaded to the appropriate mass and tire pressures set accordingly. The roller is then towed up and down the strip with a spacing of one third the wheel track (approx. 1.4 m) between wheel ruts. The number of passes required to cover an 80- x 3000-m runway is about 28, and for a towing speed of 5 kph the total time is 17 hours. This pattern of proof rolling should show up any problem areas which can then be investigated and reworked.

Proof rolling should be part of the general maintenance operation where new snow is compacted onto an existing proven pavement. In this case the spacing between passes could be about the wheel track, i.e. 4.3 m. The number of passes required to

cover an 80-m pavement width is about 10, which will take about 6 hours for a strip length of 3 km and a speed of 5 kph.

## LOGISTIC SUPPORT

For inland sites a compacted-snow runway will generally be close to the station it is to serve. In this case the support for the runway construction and maintenance needs to be grafted into the existing station operation.

On the other hand, coastal Antarctic stations are generally sited on ice-free exposed rock sites, and the runway needs to be constructed some tens of kilometers away. Temporary but reusable camp facilities should be set up each operating season at the runway site.

Manpower requirements will be dictated by the speed with which the work is to proceed. The minimum requirement is:

|                           |    |
|---------------------------|----|
| engineer in charge        | 1  |
| surveyor                  | 1  |
| test engineer/technician  | 1  |
| mechanics/plant operators | 4. |

Additionally, for an on-site camp:

|                   |    |
|-------------------|----|
| cook              | 1  |
| plumber/carpenter | 1. |

The basic equipment requirements include:

- Caterpillar D7 LGP tractor
- Heavy towed compaction roller
- Caterpillar 943 LGP tracked loader
- Caterpillar 14G road grader
- Laser leveling equipment for grader
- Two D5 tractors
- Proof roller
- On-site coldroom laboratory
- Over-snow transport.

## ON-SITE DEVELOPMENT WORK

Snow is not a conventional construction material, and although success has been amply demonstrated in constructing pavements for heavy aircraft, the technology for snow pavement production is still evolving. The experience of field workers actually engaged in the runway construction and testing work is crucial to the development of a technology that can routinely produce snow pavement of predictable quality.

There is a definite place for on-site experiment and development that verifies or refutes suggested

methods of operation. Development work can perhaps best be conducted on areas say about 20 x 300 m. This size is about 1/40 of an 80- x 3000-m runway and yet tests the production methods at full scale. The experience gained in the small areas may significantly reduce the total construction time.

Antarctic field conditions suggest that simple methods of operation are to be preferred over more complicated ones that hold promise of some benefit. It is an unusual environment to work in, and operating methods that promote teamwork and a single purpose will win the dedication of team members. This means that the whole operation needs to be intelligible to all site personnel.

It is not unusual in Antarctica to find people operating very effectively outside their official qualifications. This means that each operating team will develop idiosyncrasies that cannot be foreseen prior to the field activity. It is very important that the transfer of the field experience to other interested parties is not hindered by what seems peculiar to one construction team. Information transfer is vital to the development of snow runway technology because of the remoteness of the sites. Training for incoming personnel can only realistically be undertaken on-site, and this means that there needs to be a mix of experienced and new personnel on-site.

These aspects of construction management can be summarized in this way:

- Develop on-site methods that work for the task at hand;
- Disseminate construction experience; and
- Pass on specific site experience to incoming construction personnel on-site.

In this way, the technology of compressed snow runways can progress in an efficient manner.

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